COMPARISON OF F-15E AND F-16 DYNAMIC TARGETING
PERSISTENCE IN A FUEL-LIMITED
ENVIRONMENT

A thesis presented to the Faculty of the U.S. Army
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MASTER OF MILITARY ART AND SCIENCE
General Studies

by

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The United States Air Force (USAF) has developed the ability to strike newly detected targets within minutes by pre-positioning aircraft near potential targets. This "dynamic targeting" process provides responsiveness and flexibility, but it also has limitations. In order to strike a newly emerged target, an appropriately armed aircraft must be available to provide the desired effects. Such availability requires loitering, and limited fuel access could severely restrict loiter time near potential target areas.

Faced with such limitations, commanders desire maximum airborne presence of suitably equipped aircraft to hold targets at risk--in other words, to provide "targeting persistence." Many accept the F-15E Strike Eagle as the USAF's most capable fighter for this role due to its ability to deliver a wide variety and large quantity of munitions, its large combat radius, and its ability to loiter for hours before refueling. However, in a fuel-limited scenario, the more fuel-efficient F-16 Fighting Falcon may provide greater persistence.

This thesis proposes techniques to quantify persistence and determines whether, with a limited amount of fuel, a strike force comprised of F-16 aircraft can provide greater dynamic targeting persistence than a force comprised of F-15E aircraft.

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ABSTRACT

COMPARISON OF F-15E AND F-16 DYNAMIC TARGETING PERSISTENCE IN A FUEL-LIMITED ENVIRONMENT, by Major Brian Farrar, USAF, 106 pages.

The United States Air Force (USAF) has developed the ability to strike newly detected targets within minutes by pre-positioning aircraft near potential targets. This "dynamic targeting" process provides responsiveness and flexibility, but it also has limitations. In order to strike a newly emerged target, an appropriately armed aircraft must be available to provide the desired effects. Such availability requires loitering, and limited fuel access could severely restrict loiter time near potential target areas.

Faced with such limitations, commanders desire maximum airborne presence of suitably equipped aircraft to hold targets at risk--in other words, to provide "targeting persistence." Many accept the F-15E Strike Eagle as the USAF's most capable fighter for this role due to its ability to deliver a wide variety and large quantity of munitions, its large combat radius, and its ability to loiter for hours before refueling. However, in a fuel-limited scenario, the more fuel-efficient F-16 Fighting Falcon may provide greater persistence.

This thesis proposes techniques to quantify persistence and determines whether, with a limited amount of fuel, a strike force comprised of F-16 aircraft can provide greater dynamic targeting persistence than a force comprised of F-15E aircraft.

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I dedicate this thesis to Airmen in combat who are converting theory into airpower as I enjoy the comfortable privilege of converting thoughts into theory.

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ACRONYMS

AAR   Air-to-air Refueling

AFDD   Air Force Doctrine Document

ALSA   Air-Land-Sea Application Center

C2   Command and Control

CFT   Conformal Fuel Tank

DPI   Desired Point of Impact

F2T2EA   Find-Fix-Track-Target-Engage-Assess

GPS   Global Positioning System

ISR   Intelligence, Surveillance, and Reconnaissance

JDAM   Joint Direct Attack Munition

JFACC   Joint Force Air Component Commander

JFC   Joint Force Commander

JP   Joint Publication

KTAS   Knots True Airspeed

LGB   Laser Guided Bomb

LOCPAD   Low-Cost Persistent Area Dominance Design

MTTP   Multi-Service Tactics, Techniques and Procedures

TST   Time Sensitive Targeting

TTP   Tactics, Techniques and Procedures

UAS   Unmanned Aerial System

US   United States

USAF   United States Air Force

X-AI   Airborne Alert, Air Interdiction

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CHAPTER 1

INTRODUCTION

During the afternoon of 7 June 2006, two United States Air Force (USAF) F-16 pilots were performing a routine surveillance mission over an area northeast of Baghdad, Iraq. Their assigned task was to detect improvised explosive devices that may have been planted within their area of operations. A few hours into the mission, the pilots completed their second air refueling and were instructed to stand by for a new tasking rather than return to base as planned. At "approximately 6:11 p.m. local time," the flight lead was instructed to strike the newly detected safe house of Abu Musab al Zarqawi, Al Qaeda's top leader in Iraq at the time. Following the detailed transfer and authentication of targeting instructions, the pilot first released a GBU-12 laser-guided bomb and then a GBU-38 Joint Direct Attack Munition (JDAM), each of which had been loaded for just such a contingency (Caldwell 2006, 3). With careful planning, effective command and control, and good tactical execution, a key target was successfully struck using the USAF's recently developed "dynamic targeting" process. In this example, appropriately armed aircraft were readily available to the Joint Force Commander (JFC) when a time-sensitive target presented itself.

The 2006 Zarqawi strike represents a dynamic targeting success story. However, consider the consequences if the pilots had been flying F-15E Strike Eagles, which require more fuel than an equivalent number of F-16 Fighting Falcons, but were limited to the same amount of fuel used by the F-16s on that day. Would the F-15E aircraft loaded with appropriate munitions have to return to base due to a lack of available fuel before the target could emerge for destruction? During Operation Iraqi Freedom, fuel

availability had not been a limiting factor in allocating aircraft to dynamic targeting operations, but one cannot discount the possibility of a future fuel-limited scenario. This thesis will compare dynamic targeting persistence capabilities of USAF fighters in a fuel-limited environment.

<div align="center">Dynamic Targeting Defined</div>

To understand dynamic targeting and appreciate the process' responsiveness, one must first understand "deliberate targeting," which has been the normal mode of operations for decades. Joint Publication (JP) 3-60, *Joint Targeting,* describes deliberate targeting as the process which "prosecutes planned targets that are known to exist in the operational environment with engagement actions scheduled against them to create the effects desired to support achievement of JFC objectives" (JP 3-60 2007, vii). More simply-- air component personnel systematically develop targets, assign forces, plan and execute missions, and analyze performance. This deliberate targeting cycle is a continually recurring event as depicted in figure 1. For air operations, the deliberate targeting process typically requires approximately seventy-two hours from target development to post-strike battle damage assessment (AFDD 2-1.9 2006, 25).

Although the deliberate targeting process has always accommodated target additions or changes during the planning phase, such "pop-up" targets have proven extremely difficult--often impossible--to prosecute once the strike package departed for the planned mission. Planners would typically assign the newly developed target(s) to aircrews accomplishing strikes during the next cycle. The USAF overcame this lack of short-term flexibility by developing the dynamic targeting process.
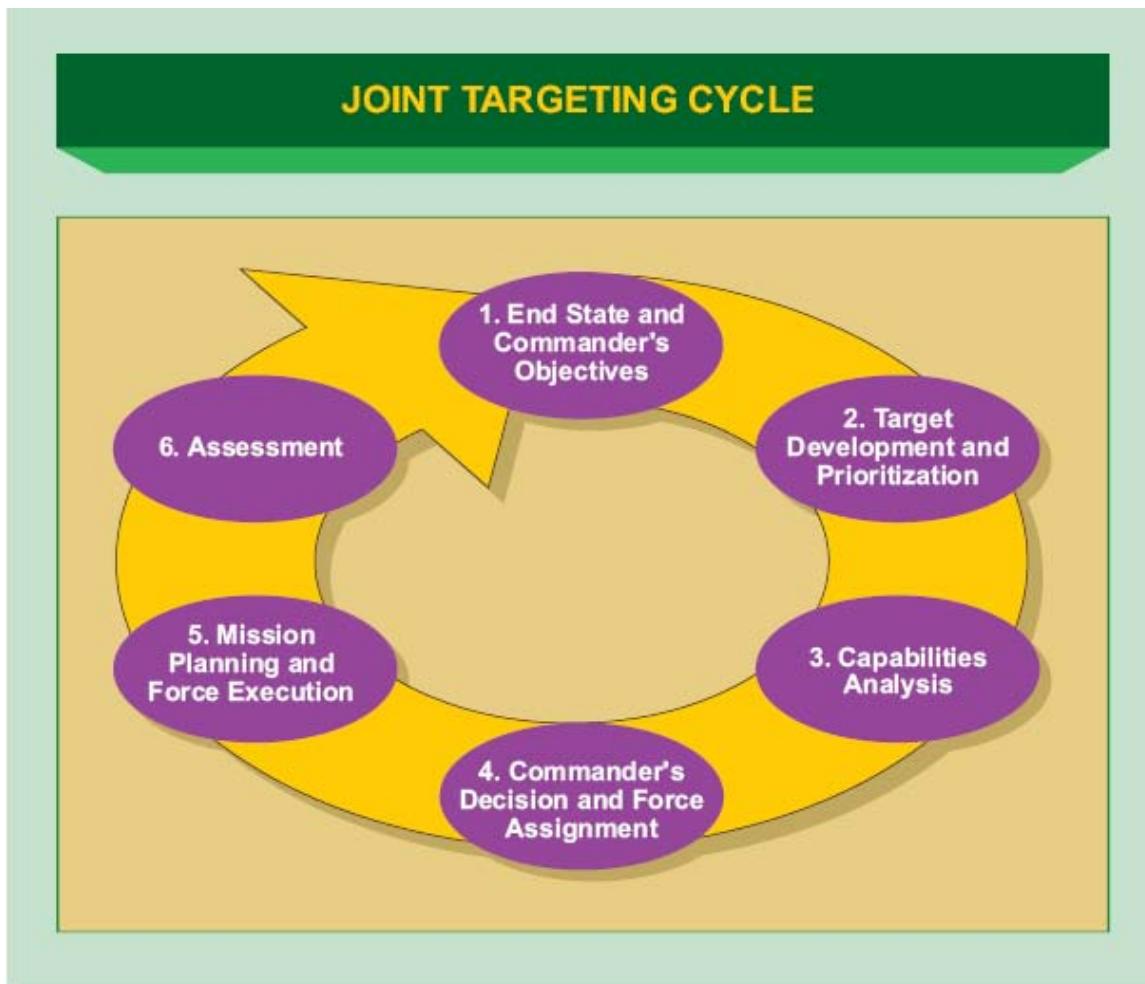
Figure 1.   The Joint Targeting Cycle
Source: Chairman, Joint Chiefs of Staff, Joint Publication (JP) 3-60, *Joint Targeting* (Washington, DC: Government Printing Office, 2007), II-3, http://www.dtic.mil/doctrine/jel/new_pubs/jp3_60.pdf, (accessed 17 May 2007).

JP 3-60 defines dynamic targeting as the process that "prosecutes targets identified too late, or not selected for action in time to be included in deliberate targeting" (JP 3-60 2007, GL-7). In order to have assets available to strike emerging targets on short notice, the Joint Force Air Component Commander (JFACC) can either pre-position aircraft over potential target areas or divert airborne aircraft already performing duties assigned during the deliberate targeting process. Dynamic targeting saves time normally

consumed by general planning, ground operations, and target area ingress which are tasks

that aircrews accomplish after target emergence during the deliberate targeting process.

With dynamic targeting, however, aircrews have accomplished these tasks prior to target

emergence. Dynamic targeting is loosely analogous to a fully geared firefighting crew

driving around the city to decrease response time when the dispatcher assigns a tasking.

Figure 2 depicts a graphic correlation of deliberate and dynamic targeting.
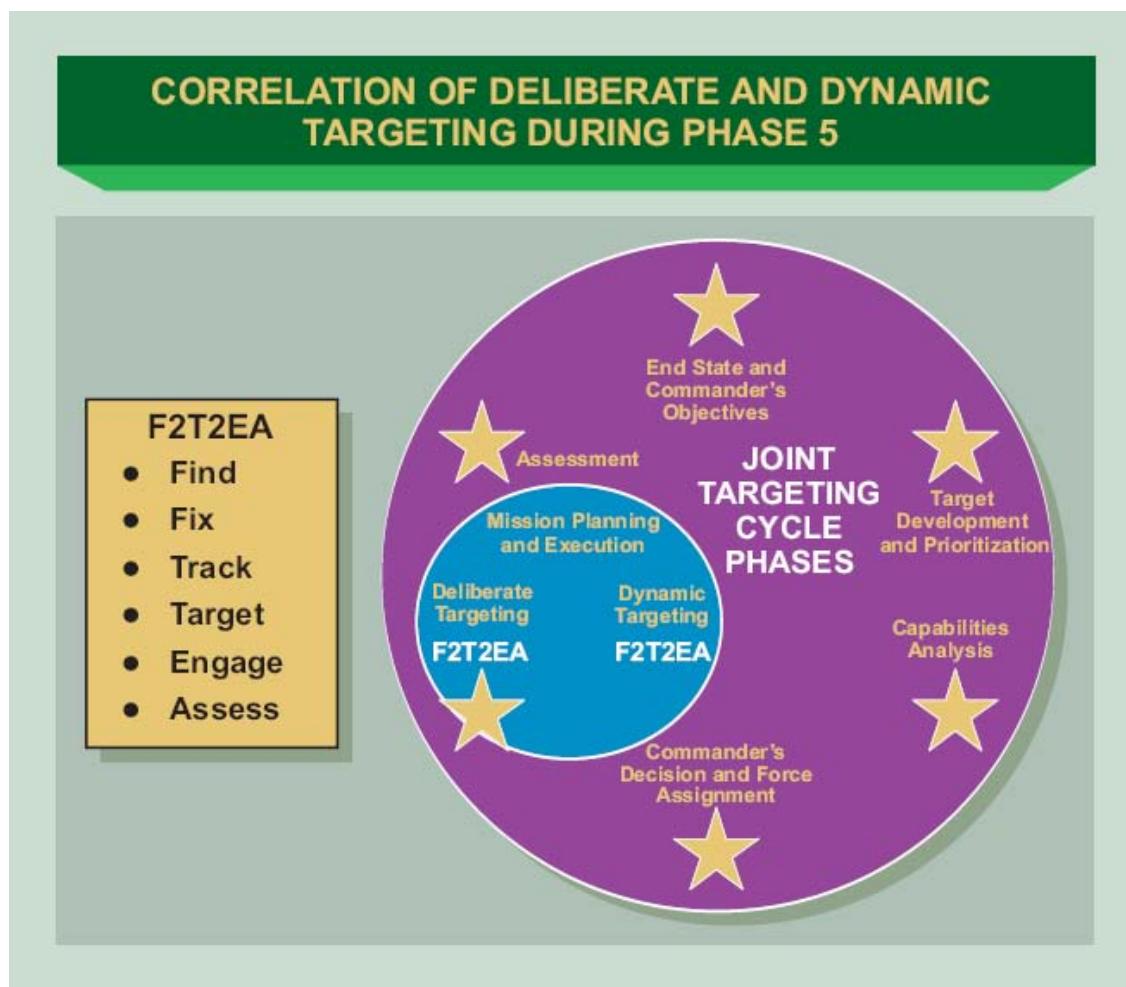
Figure 2.   Correlation of Deliberate and Dynamic Targeting During Phase 5
*Source*: Chairman, Joint Chiefs of Staff, Joint Publication (JP) 3-60, *Joint Targeting* (Washington, DC: Government Printing Office, 2007), II-3, http://www.dtic.mil/ doctrine/jel/new_pubs/jp3_60.pdf, (accessed 17 May 2007).

A JFACC typically prosecutes time sensitive targets (TSTs) using the dynamic targeting process. A TST is defined as: "a JFC designated target or target type of such high importance to the accomplishment of the JFC's mission and objectives or one that presents such a significant strategic or operational threat to friendly forces or allies, that the JFC dedicates intelligence collections and attack assets or is willing to divert assets away from other targets in order to find, fix, track, target, engage and assess it" (JP 3-60 2007, I-5). Dynamic targeting provides a highly effective means to address TSTs. In fact, the close relationship between dynamic targeting and TST often causes people to treat the two terms synonymously. TST using air strike is, more accurately, a subset of dynamic targeting because not all dynamic targets are time sensitive.

A variety of air assets can conduct dynamic targeting attacks. As shown in figure 3, forces must complete the entire "find, fix, track, target, engage, assess" (F2T2EA) process to succeed; this requires sensor-shooter coordination. An intelligence, surveillance, and reconnaissance (ISR) sensor must find, fix, and track a target; a shooter must engage the target; and an ISR platform must assess performance. Most often, the ISR sensor and the shooter are two separate entities. Examples of ISR assets include reconnaissance aircraft, satellite systems, human intelligence, and unmanned aerial systems (UASs). Examples of shooter assets include fighter aircraft, bomber aircraft, cruise missiles, and UASs.

To prevent delays associated with sensor-shooter coordination, the USAF desires sensor-shooter fusion, the combination of sensor and shooter in one platform. Though the Zarqawi strike was accomplished with separate ISR and attack platforms, the F-16 pilots who conducted the strike were diverted from a mission on which they would act as both

sensor and shooter in the F2T2EA process. Using targeting pods to detect improvised explosive devices, the pilots would coordinate an attack using dynamic targeting processes, utilizing their F-16s as both ISR sensor and shooter platforms in the F2T2EA sequence (Caldwell 2006, 2). The unmanned combat aerial vehicle, which provides not only cutting-edge ISR capability but also the ability to attack targets, will provide the USAF a persistent sensor-shooter platform for future "dull, dangerous, and dirty" dynamic targeting missions (Marzolf 2004, 35).
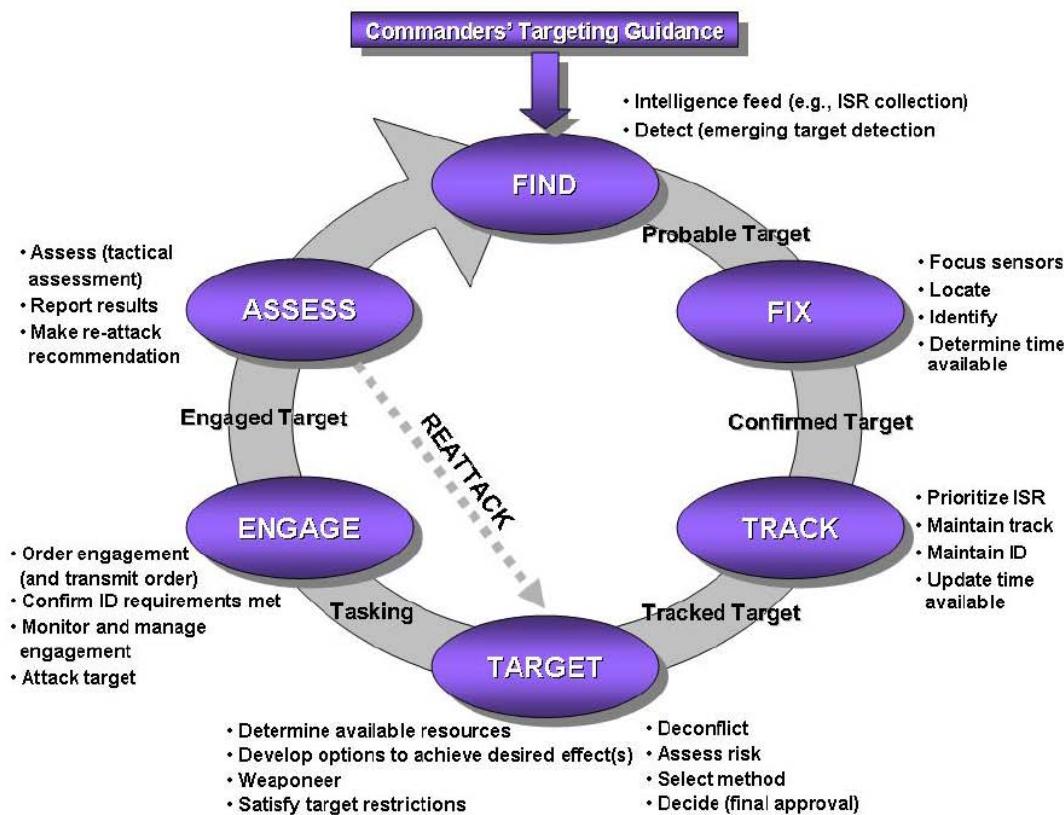
Figure 3.   The Dynamic Targeting Process
Source: Department of the Air Force, Air Force Doctrine Document (AFDD) 2-1.9, *Targeting* (Washington, DC: Government Printing Office, 2006), 49, http://www.e-publishing.af.mil (accessed 19 March 2007).

Dynamic Targeting Limitations

Though it provides significant flexibility to the JFC, dynamic targeting also has limitations. If a time-sensitive target emerges and the JFC directs a strike, then an appropriately armed aircraft must be available to attack. In most air combat scenarios, "available" implies that the aircraft is airborne near the target.

With such limitations, the JFACC wishes to maximize airborne presence of suitably equipped aircraft to perform dynamic targeting missions; in other words, provide "targeting persistence." Neither joint doctrine nor USAF doctrine currently defines persistence relative to targeting vulnerability. This thesis defines dynamic targeting persistence as the cumulative period during which an aircraft can access an area and provide desired effects. A high level of targeting persistence means that a force can hold targets at risk for a long period.

Aircraft can provide persistence in two ways: (1) airborne presence near a target area or (2) ground alert presence near a target area. As discussed previously, aircraft that are either pre-positioned over the battlefield or diverted from another mission provide airborne persistence. However, aircraft and crews on ground alert can also provide persistence if their departure airfield is close enough to hold targets at risk, but such a scenario is typically the exception. Even with close proximity to targets, the quickest of aircrew "alert scrambles" may not allow forces to attack the target(s) within the JFACC's time constraint, particularly considering that the USAF goal for dynamic targeting capability is "to strike mobile and emerging targets in fewer than 10 minutes" (Hebert 2003, 50). This thesis focuses only upon airborne persistence since fuel availability does

not influence ground alert time--fighter aircraft consume no fuel when sitting on the ground with engines not running.

Providing persistence by pre-positioning fighters over the battlefield requires aircraft loitering (also known as "holding"), and limited access to in-flight refueling could severely restrict loiter time over potential target areas. Many consider the F-15E Strike Eagle to be the USAF's most capable fighter for this type of mission due to its ability to deliver a wide variety and large quantity of munitions, its large combat radius and its ability to loiter for hours before refueling. If fuel is not a limiting factor, the F-15E can hold more potential targets at risk than the F-16 simply because it flies further and carries more bombs per aircraft. However, in a fuel-limited scenario, planners may have to consider utilizing the much more fuel efficient F-16 Fighting Falcon for dynamic targeting.

Air forces could lack fuel availability for many reasons including a provider's inability to supply or distribute. Supply challenges could result from lack of raw resources, inability to produce at a pace required for major war, or destruction of existing fuel stores by the enemy. Distribution challenges could include lack of air refueling aircraft, lack of mass fuel stores during the logistics build-up phase of a conflict, or limited air-to-air refueling (AAR) offload quantities associated with long flight distances. In recent conflicts, particularly those near fuel-rich allies, United States (US) air planners have not needed to consider fuel efficiency when selecting aircraft for dynamic targeting missions thanks to robust resource availability. Other considerations such as fighter squadron deployment rotations and aircraft basing agreements have driven aircraft availability for dynamic targeting allocation. However, a mission's success in a fuel-

limited scenario could depend upon allocating aircraft that can maximize loiter time, and thus persistence, with a given amount of fuel.

Primary Research Question

The primary research question is: With a limited amount of fuel, can a strike force comprised of F-16 aircraft provide greater dynamic targeting persistence than a force comprised of F-15E aircraft?

For this study, availability of "a limited amount of fuel" means that a finite (and less-than-desirable) fuel quantity is available for an assigned mission. Though dynamic targeting can be accomplished by B-1, B-2, and B-52 bombers, A-10 attack aircraft, US Navy F/A-18 fighters, MQ-9 UASs, and other platforms, the scope of this thesis is limited to F-15E and F-16 aircraft, which are the Air Force's current fighters typically tasked with dynamic targeting missions.

Secondary Research Questions

In order to compare two systems as described above, one must first quantify the persistence capability of each system, requiring an answer to the following secondary research question: Is dynamic targeting persistence quantifiable? To address this question, the analysis identifies key variables to consider when confronted with a particular dynamic targeting scenario and provides a deliberate methodology with which planners can input available fuel quantity, aircraft performance characteristics, and other variables to quantify the maximum dynamic targeting persistence capability of a given strike force. The resulting formula is also valuable in calculating persistence capabilities of other aircraft systems, whether manned or unmanned.

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To calculate persistence and make the primary research comparison, one must apply values to the persistence formula, requiring the researcher to answer the following research question: What are the capabilities and characteristics of F-15E and F-16 fighter aircraft? This study identifies aircraft capabilities and characteristics including fuel capacity, fuel consumption rates, combat radius, and weapons payloads in order to quantify persistence. These aircraft capabilities are sourced from unclassified data. For the purposes of this comparative research, understanding the relationship between F-15E and F-16 aircraft capabilities is more important than knowing the exact limits of their capabilities.

<u>Significance of this Research</u>

This research provides planners a useful methodology with which to quantify a force's maximum dynamic targeting persistence, and it identifies whether a force comprised of F-15E or F-16 aircraft would be more appropriate if faced with a potentially fuel-limited scenario. The study also identifies key factors to consider when assessing dynamic targeting persistence capabilities.

CHAPTER 2

REVIEW OF LITERATURE

The USAF has executed dynamic targeting missions for less than a decade, and the volume of associated literature is relatively small. Previously, warfighters could not detect and identify an emerging target routinely, maintain track while prioritizing the target rapidly, determine available resources, de-conflict airborne assets, determine appropriate weapons, and pass command and control data to a selected strike aircraft within a short enough period to make aircraft allocation (and, therefore, doctrine development) for dynamic targeting worthwhile. Prior to the existence of dynamic targeting doctrine, aircrews have occasionally engaged and destroyed targets of opportunity, but these encounters were typically secondary to accomplishing another assigned mission.

Doctrinal Publications

Air Force Doctrine Document (AFDD) 2-1.9, *Targeting*, last updated on 8 June 2006, provides the most comprehensive doctrinal discussion of dynamic targeting processes. It was the first doctrinal publication to provide detailed dynamic targeting procedures, dedicating an entire chapter to the topic. Chapter 3, "Dynamic Targeting," begins with a general discussion of roles and responsibilities for combined air operations center personnel who perform dynamic targeting actions. These personnel coordinate actions required to complete the F2T2EA cycle and enable aircrews to successfully strike targets. Next, the chapter highlights categories of targets prosecuted using dynamic targeting. These include: (1) time-sensitive targets, (2) high payoff targets, (3) preplanned

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targets whose status has changed in some way, and (4) targets that "friendly commanders deem worthy of targeting . . . which will not divert resources from higher-priority targets" (AFDD 2-1.9 2006, 48). Joint doctrine defines a high payoff target as "a target whose loss to the enemy will significantly contribute to the success of the friendly course of action" (JP 1-02 2007, 239). AFDD 2-1.9 also provides an expanded discussion of the F2T2EA process described in chapter 1 of this thesis and presents other considerations for dynamic targeting execution. Those considerations include designating engagement authority, managing increased risk during dynamic targeting operations, handling changes, understanding limitations associated with reduced planning time, and outlining unit-level targeting responsibilities.

The recently released version of JP 3-60, *Joint Targeting,* (13 April 2007) contains increased discussion of dynamic targeting as compared to the previous version, published in 2002. The revised content closely resembles that of AFDD 2-1.9, which JP 3-60 identifies as a source, except that JP 3-60 expands the F2T2EA description outlined in AFDD 2-1.9. This is not surprising since JP 3-60 must address kill chain considerations for all services. In addition, the latest version of *Joint Targeting* delineates target categories and target types clearly, as shown in figure 4 (JP 3-60 2007, I-7). This delineation is important because it provides multiservice warfighters a common ground when categorizing targets and deciding whether deliberate or dynamic targeting is more appropriate. As now defined in joint doctrine, the two types of planned targets are:

1. Scheduled Target. "Planned target upon which fires or other actions are scheduled for prosecution at a specific time" (JP 3-60 2007, GL-12).

2. On-Call Target. "Planned target upon which fires or other actions are determined using deliberate targeting and triggered, when detected or located, using dynamic targeting" (JP 3-60 2007, GL-11).

The two types of targets of opportunity are:

1. Unplanned Target. "A target of opportunity that is known to exist in the operational environment" (JP 3-60 2007, GL-15).

2. Unanticipated Target, "A target of opportunity that was unknown or not expected to exist in the operational environment" (JP 3-60 2007, GL-15).

Note that JP 3-60 does not designate "time-sensitive" target as a stand-alone category or type of target. Any of the target types described in figure 4 can be time-sensitive, which will influence the means of prosecution. This thesis addresses persistence capabilities against planned on-call targets, unplanned targets of opportunity, and unanticipated targets of opportunity.
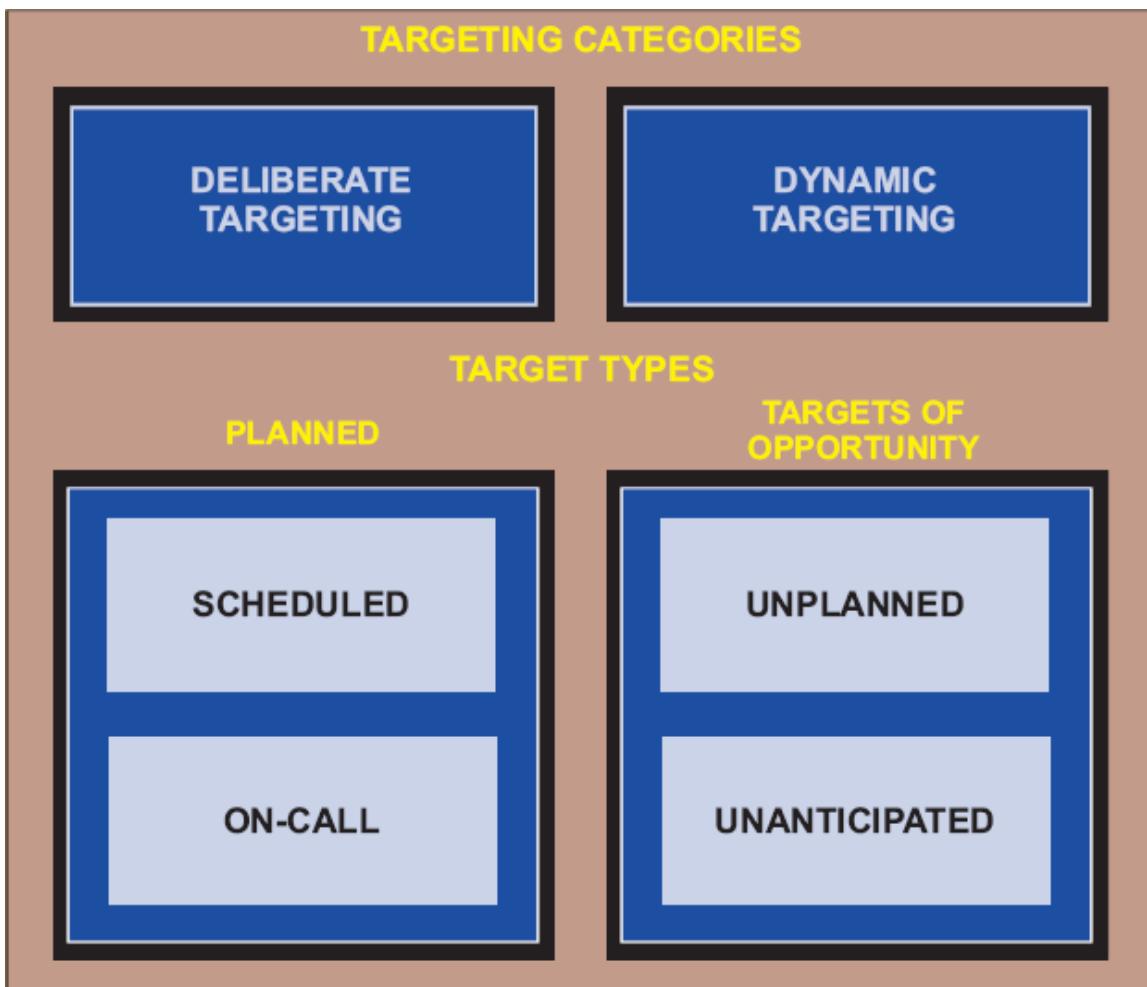
Figure 4. Target Categories and Target Types
Source: Chairman, Joint Chiefs of Staff, Joint Publication (JP) 3-60, *Joint Targeting* (Washington, DC: Government Printing Office, 2007), I-7, http://www.dtic.mil/ doctrine/jel/new_pubs/jp3_60.pdf (accessed 17 May 2007).

JP 3-60 provides the warfighter a good understanding of dynamic targeting's

nature, but offers little in describing how to execute the process. Tactics, techniques, and

procedures (TTPs) for execution are scattered throughout many different volumes of

service doctrine, which hinders coordination capability, and varying levels of

classification further complicate the matter. Since TSTs provide some of the most

difficult targeting problems due to their requirement for rapid, coordinated, inter-service

action, the Air-Land-Sea Application Center (ALSA) has developed *TST: Multi-Service Tactics, Techniques, and Procedures* [MTTP] *for Targeting Time-Sensitive Targets* (April 2004). The manual "provides the JFC, the JFC operational staff, and components an unclassified TTP to coordinate, deconflict, synchronize, and prosecute TSTs within any operational area" (ALSA 2004, i). ALSA is a joint, cross-departmental organization chartered by the four services for rapid response to service interoperability issues and has a reputation for providing useful and practical products to the warfighter--this MTTP is no exception. It "highlights recent time-sensitive targeting tactics, techniques and procedures commonalities; presents best practices; and includes key lessons-learned from events such as Operation Allied Force, Millennium Challenge 2002, Operation Enduring Freedom, and Operation Iraqi Freedom. It discusses the TST process, multiservice time-sensitive targeting command and control (C2), commander's guidance, planning, coordination (including procedures for a Common Geographic Reference System), organization, training and execution procedures" (ALSA 2004, i). The manual "includes component and service time-sensitive targeting procedures, multi-national considerations, time-sensitive targeting checklist samples, discusses TST attack, intelligence, surveillance, and reconnaissance assets, and collaborative tools and their associated TTPs" (ALSA 2004, i). Though it does not encompass all aspects of dynamic targeting, this manual is an essential product for any warfighter commanding, planning, or executing TST missions. Despite its value as a practical guide, the ALSA MTTP, like other doctrinal publications, does not directly address persistence.

Most non-doctrinal publications focus upon TST considerations in dynamic targeting and do not address fuel-limited scenarios. Typical articles present technological challenges and successes in compressing the F2T2EA "kill chain" and highlight the interfaces between ISR assets, C2 systems, and attack platforms. Examples of such works include Adam J. Hebert's *Air Force Magazine* article entitled "Compressing the Kill Chain" (March 2003) and Ted McKenna's *Journal of Electronic Defense* article entitled "Right on Time" (April 2005). Both provide a good overview of TST issues and the capabilities and limitations of US forces relative to TST execution.

In 1999, Major Kevin Fox, USAF, provided a comprehensive research report entitled "Dynamic Targeting: Are We Ready?" As the title implies, his thesis proposed that, as of 1999, "there may not be enough delineated procedures for dynamic targeting or sufficient training to prosecute the threat effectively." In his research, Fox examines planning and targeting procedures, C2 processes, assets available for dynamic targeting, and training procedures. Neither the definition of dynamic targeting nor its relationship to the F2T2EA process were well developed at the time, and in describing them to his readers the author stated that "dynamic targeting will be used synonymously with time-critical targets [later re-designated time-sensitive targets]" (Fox 1999, 2). This is no longer doctrinal since dynamic targeting is also used against non-TSTs. Despite expected inconsistencies with current doctrine, Fox's thesis provides analysis and raises questions that are directly applicable to current dynamic targeting practices. In his conclusion, the author does not directly answer the primary research question (are we ready for dynamic targeting?). Rather, he states that his purpose "was to highlight the need for dynamic

targeting considerations, demonstrate the amount of coordination and training required to accomplish this mission, highlight some of the forces available to support dynamic targeting, then look at the training required" to accomplish the dynamic targeting mission (Fox 1999, 33). The USAF has addressed most of those issues during the eight years since his research.

In 2002, Major John McDonnell, USAF, proposed that "the JFC should avoid apportioning assets solely to TST prosecution," but rather should "direct components to develop flexible, responsive processes to divert assets from lower-priority previous tasking when TSTs are discovered" (2002, 2). He presented this proposal in his Naval War College thesis, "Apportion or Divert? The JFC's Dilemma: Asset Availability for Time-Sensitive Targeting," dated 4 February 2002. The decision regarding which method to use for dynamic targeting--apportioning dedicated assets or diverting previously tasked assets--remains today. Apportionment for dynamic targeting, now called X-AI (airborne alert air interdiction), is the previously unimaginable option of launching aircrews for combat interdiction missions with bomb-laden aircraft and no assigned targets. However, in addition to aircraft apportioned for X-AI taskings, aircraft accomplishing deliberate targeting missions also provide dynamic targeting persistence because they can also access an area and provide desired effects other than those already planned. McDonnell proposes that diverting aircraft to strike targets of higher priority than those previously assigned "appears to offer the best solution" to the dynamic targeting problem (2002, 19). In recent operations, JFACCs have typically combined apportionment and diversion techniques to maximize dynamic targeting persistence. The comparison in this thesis of

F-15E and F-16 aircraft in a fuel-limited environment focuses upon airborne alert forces apportioned specifically for dynamic targeting.

In March 2004, Major Gregory Marzolf of the USAF School of Advanced Airpower Studies completed a significant study related to dynamic targeting. In "Time-Critical Targeting--Predictive versus Reactionary Methods: An Analysis for the Future," he discusses the importance of persistence over the battlefield for time-critical operations and proposes more efficient methods to achieve persistence in the future. He introduces and investigates two methods of dynamic targeting execution: "reactive" and "predictive" (2004, v). The USAF currently uses a reactive approach as defined by Marzolf, "which first detects a target with an ISR platform and tasks a loitering strike platform to kill it" (2004, v). The author proposes that this method is inefficient for weapons delivery platforms, which are often geographically distant from detection platforms and possess inefficient sensor-shooter coordination. Marzolf also observes that "manned strike aircraft lack persistence" (2004, 48) and that "manned aircraft are poorly used in the [TST] role because of efficiency constraints" (2004, 61). However, rather than analyzing persistence capabilities of current aircraft, Marzolf proposes techniques for predictive methods of "deploying weapons in likely target areas before they emerge," especially in deep or hostile areas where conventional aircraft cannot loiter for long periods (2004, v). He further proposes development of future ISR platforms that will also be able to identify and strike targets, thus reducing inefficiencies associated with inter-platform communication and coordination requirements. An example of such an area dominance system is the LOCPAD (Low-Cost Persistent Area Dominance Design), conceptualized by Air Force Research Laboratories (see figure 5). LOCPAD is a combination sensor-

shooter platform with a twelve-hour loiter capability. Marzolf concludes that the USAF

should develop such systems to accomplish dynamic targeting missions in the future, but

in the meantime, "the USAF should continue pursuing the reactionary approach" (2004,

66). Persistence measurement techniques developed in the following analysis can help

planners optimize future dynamic targeting capabilities.
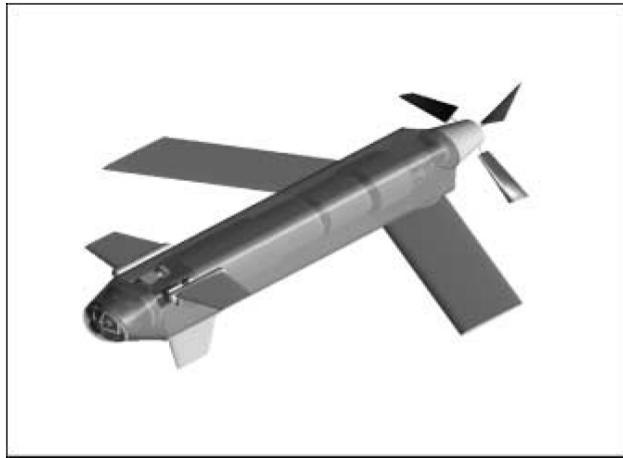
Figure 5.   Low-Cost Persistent Area Dominance Design
Source: Gregory S. Marzolf, "Time-Critical Targeting--Predictive Versus Reactionary
Methods: An Analysis for the Future" (Master's thesis, Air Command and Staff College.
2004), 52, http://maxwell.af.mil/au/aul/aupress/saas_Theses/Marzolf/Marzolf.pdf
(accessed 25 March 2007).

This research revealed no existing literature that directly defines dynamic

targeting persistence, contains a methodology to quantify persistence, or compares F-15E

and F-16 persistence capabilities.

CHAPTER 3

METHODOLOGY

This research analyzes the dynamic targeting capabilities of notional F-15E and

F-16 strike packages to determine which force could provide greater persistence given a

limited amount of fuel. In order to answer the research questions, the research design

includes two sequential steps: (1) development of a methodology to measure persistence,

and (2) comparison of F-15E and F-16 strike forces given various fuel-limited scenarios

(see figure 6).
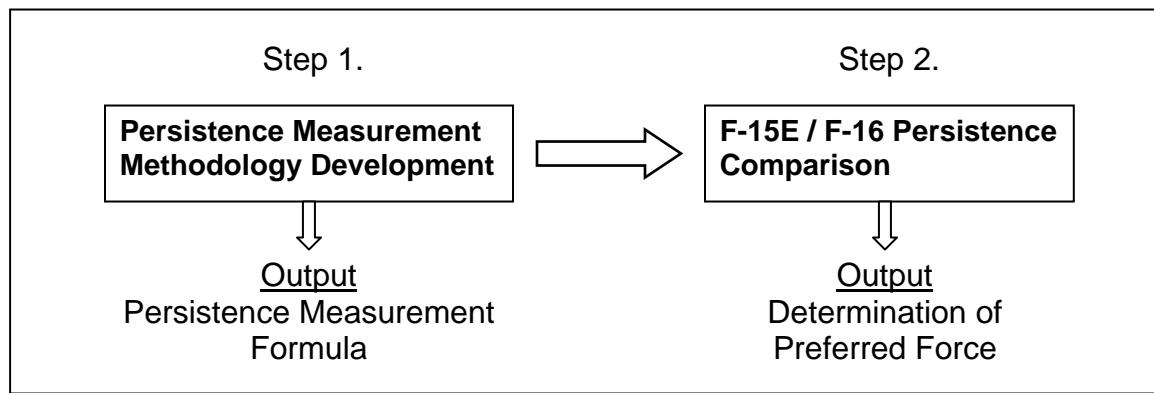
Figure 6.   Research Design

Step 1: Development of Persistence Measurement Methodology

The first step in the research design produces a quantitative methodology to

calculate the dynamic targeting persistence capability of a given force. As defined in

chapter 1, persistence is the cumulative period during which an aircraft can access an area

and provide desired effects. As evidenced in this definition and illustrated in figure 7, one

must measure three characteristics to quantify persistence: (1) maximum potential on-station time, (2) maximum accessible geographic area, and (3) ability to effect targets. The methodology to measure persistence as developed during this research enables a planner to quantify each of these three factors for a given weapons system in order to compare dynamic targeting capability

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┌─────────────────────────────────────────────────────────────────┐
│                                                                   │
│  ┌──────────────────────────────┐                                 │
│  │ POTENTIAL ON-STATION TIME    │─────┐                           │
│  └──────────────────────────────┘      ▶   DYNAMIC               │
│                                                                   │
│  ┌──────────────────────────────┐          TARGETING             │
│  │ POTENTIAL AREA COVERAGE      │─────────▶  PERSISTENCE          │
│  └──────────────────────────────┘      ▶                         │
│                                                                   │
│  ┌──────────────────────────────┐                                 │
│  │ POTENTIAL EFFECTS            │─────┘                           │
│  └──────────────────────────────┘                                 │
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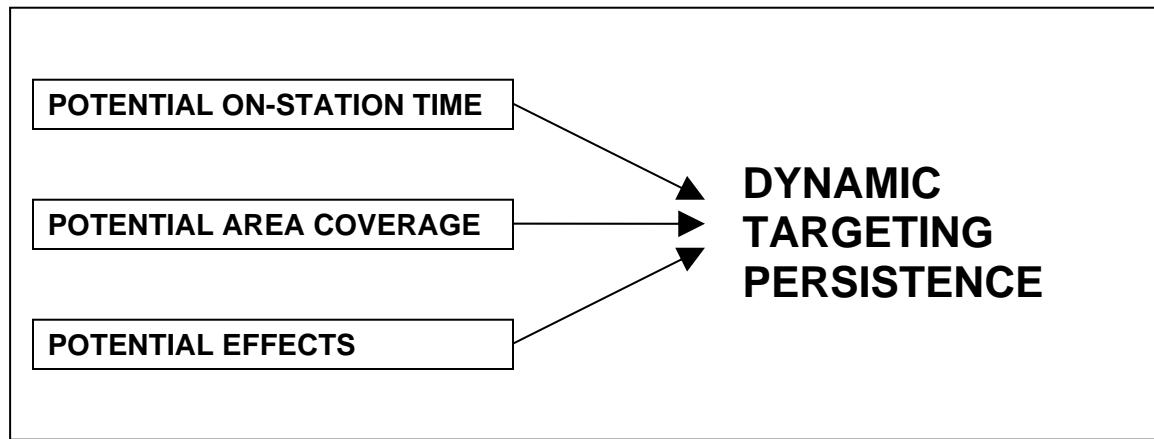
Figure 7.   Components of Persistence

The time during which an area remains vulnerable to attack is a function of the strike package's ability to loiter and attack with a given amount of fuel. The chapter 4 analysis identifies variables that influence a fighter aircraft's ability to loiter for long periods and provides an equation to calculate maximum potential time on station.

The geographic surface area accessible for dynamic targeting is a function of the number of aircraft, the combat radius of each aircraft, and the positioning of those aircraft. Additionally, unquantifiable variables such as enemy threats and adverse weather conditions influence an aircraft's ability to reach and effect targets. The analysis addresses quantitative and qualitative variables influencing persistence and provides an

equation to measure potentially accessible surface area, measured in square nautical miles (nm^2).

An aircraft's ability to effect targets is the most difficult aspect of persistence to measure. Since the persistence definition states that a force must not only be present, but also must be able to "provide desired effects," an overall measure of persistence must include weighted variables to address this capability. The chapter 4 analysis provides a quantitative system to measure each aircraft's ability to achieve dynamic targeting effects.

Finally, the three measures described above--time, area, and effects--are combined into a formula to determine notional strike forces' dynamic targeting persistence.

Step 2: Comparison of F-15E and F-16 Force Persistence

The final step in the research design applies F-15E and F-16 capability data to the formula developed in step 2 in order to compare dynamic targeting persistence. This step begins by briefly identifying F-15E and F-16 capabilities relative to dynamic targeting. Tools for evaluating capabilities and limitations include unclassified aircraft technical data (flight manuals); Air Force tactics, training, and procedure manuals; and commercially available aircraft reference publications. Given the presented scenario with limited fuel availability, the study analyzes notional forces' variables (aircraft quantity, fuel consumption rate, weapons configuration, and others) consistent with employment doctrine to quantify and compare the maximum persistence capability. The results will confirm whether a strike package comprised of F-16 aircraft can provide greater dynamic

targeting persistence than a force comprised of F-15E aircraft in an equivalent fuel-

limited scenario and will outline conditions that must be present for this to occur.

CHAPTER 4

ANALYSIS

This analysis quantifies the dynamic targeting capabilities of notional F-15E and F-16 strike packages and determines which force could provide greater persistence given a limited amount of fuel. As described in chapter 3, the analysis is accomplished in two steps: (1) development of a methodology to measure persistence, and (2) comparison of F-15E and F-16 strike forces given various fuel-limited scenarios.

Quantifying Persistence

The following section proposes a quantitative methodology to calculate the dynamic targeting persistence capability of a given force. The resulting formulas provide a way for planners to measure a force's maximum potential on-station time, maximum geographic area made vulnerable to attack, and ability to effect targets. The analysis separately considers each element of persistence--time, area, and effects--and combines the measurement processes into a format that is practical for force comparisons.

Measuring Maximum Potential On-Station Time

When an aircraft is pre-positioned in the air to provide dynamic targeting persistence, as demonstrated during airborne alert air interdiction (X-AI) as described in chapter 2, the time component of persistence is defined by the aircraft's ability to loiter over or near the enemy to allow a timely attack when a target emerges. The following analysis refers to such a period as "on-station time." JP 1-02 defines on-station time as simply "the time an aircraft can remain on-station, [which] may be determined by endurance or orders" (2007, 390). For dynamic targeting effectiveness, an aircraft must

not only be on-station but also must have appropriate fuel and munitions to accomplish one or more immediate attacks and recover to the planned airbase with appropriate fuel reserves. Initiation and termination of on-station time is scenario dependent. The following analysis assumes that on-station time initiates upon arrival at the initial loitering and refueling location and does not include the takeoff climb and departure phases of flight. On-station time includes both loitering and attack operations, and it terminates once the pilot commences recovery to home base (see figure 8). These assumptions simply allow a common baseline with which to make comparisons and, of course, can be altered for scenarios in which an aircraft has the capability to commence an attack during departure or recovery. Figures 8 and 9 depict the phases of flight commonly encountered during X-AI missions, though the duration of each phase depends upon the scenario. Later analysis will address scenario-specific considerations.
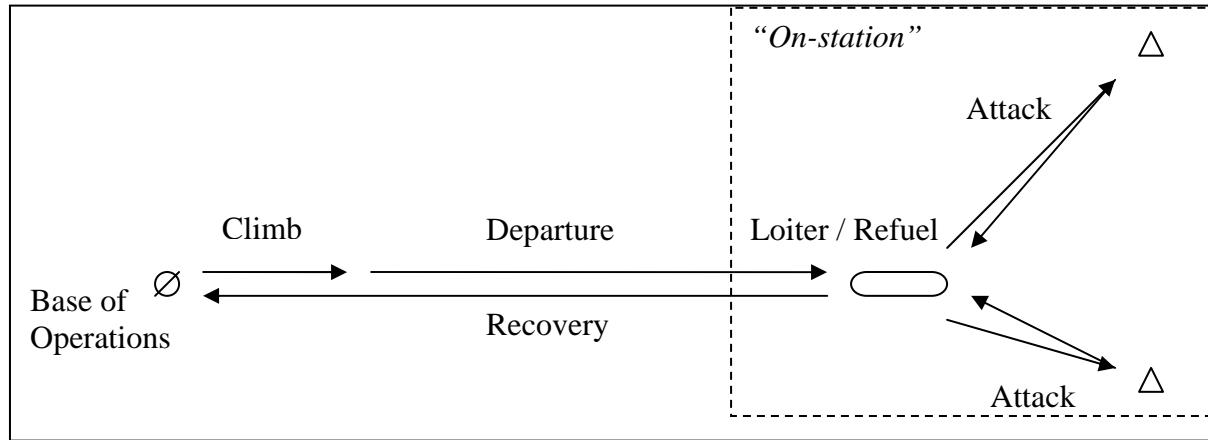
Figure 8.   Phases of a Typical Airborne Alert Air Interdiction Mission (Plan View)

Altitude Levels

High--   Departure   Loiter / Refuel

Med--   Climb   Recovery

   Attack

Low--
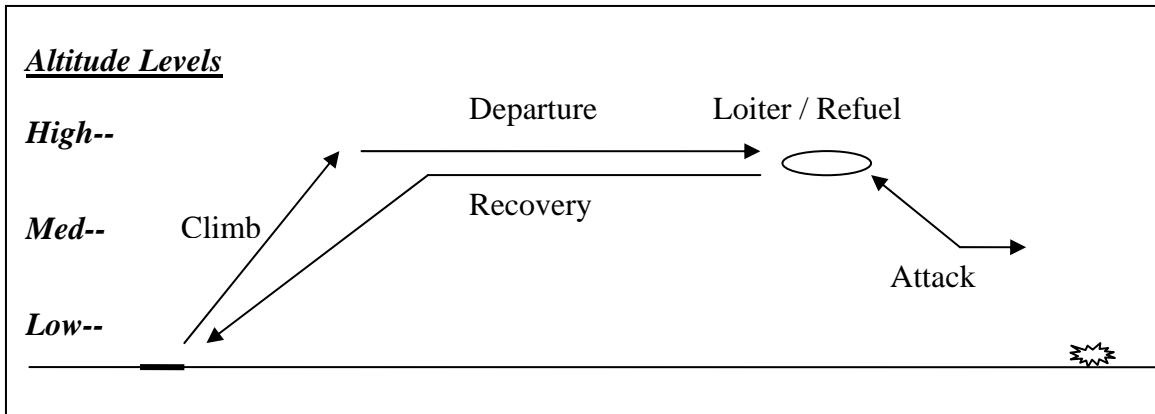
Figure 9.   Phases of a Typical Airborne Alert Air Interdiction Mission (Profile View)

Development of a practical equation to predict maximum potential on-station time will be built upon the following basic formula, which calculates on-station time using available on-station fuel quantity and average fuel consumption rate (note: all values are "per aircraft" unless stated otherwise):

$$t_{\text{on-station}} = Q_{\text{on-station}} / FF_{\text{on-station}}$$

where $t_{\text{on-station}}$ = *on-station time*

   $Q_{\text{on-station}}$ = *quantity of fuel available for on-station operations*

   $FF_{\text{on-station}}$ = *mean fuel flow during on-station operations (loiter and attack)*

For example, if an F-16 pilot accomplishing an X-AI mission has 8,000 pounds of fuel available for on-station operations (does not include fuel used or reserved for climb, departure, and recovery) and achieves an average fuel flow of 5,000 pounds-per-hour during his or her on-station operations, maximum on-station time is 1.6 hours.

$$t_{\text{on station}} = Q_{\text{on station}} / FF_{\text{on-station}} = (8{,}000 \text{ lbs}) / (5{,}000 \text{ lbs/hr}) = 1.6 \text{ hrs}$$

Of course, in practical application, one rarely knows the fuel quantity specifically available for on-station operations ($Q_{\text{on station}}$) versus "administrative" operations (climb, departure, and recovery). However, given initial fuel quantity and available quantity from air refueling, one can predict $Q_{\text{on station}}$ by analyzing fuel consumption per mission phase using the following formula:

$$Q_{\text{on-station}} = Q_{\text{total}} - Q_{\text{ground ops}} - Q_{\text{climb}} - Q_{\text{departure}} - Q_{\text{recovery}} - Q_{\text{reserve}}$$

where $Q_{\text{total}} = $ *total fuel quantity available per aircraft (initial fuel + air-received fuel)*

$Q_{\text{ground ops}} = $ *fuel quantity consumed during ground ops (engine start to takeoff)*

$Q_{\text{climb}} = $ *fuel quantity consumed during climb (takeoff to arrival at cruise altitude)*

$Q_{\text{departure}} = $ *fuel quantity consumed during departure (post-climb to on-station)*

$Q_{\text{recovery}} = $ *fuel quantity consumed during recovery (station exit to landing)*

$Q_{\text{reserve}} = $ *fuel quantity reserved for divert to an alternate airfield if required*

The value for Q_{total} is simply the overall amount of fuel available per aircraft. This dependent variable represents "a limited amount of fuel" as stated in the primary research question.

$Q_{\text{ground ops}}$ can be determined by multiplying the fuel consumption rate during ground operations by the time from engine start to takeoff as follows:

$$Q_{\text{ground ops}} = (FF_{\text{ground ops}})(t_{\text{ground ops}})$$

where $FF_{\text{ground ops}} = $ mean fuel flow during ground operations, engine start to takeoff

$t_{\text{ground ops}} = $ time consumed during ground operations, engine start to takeoff

During ground operations, idle fuel flow for each F100-PW-229 engine in an F-15E or F-16 is approximately 1,200 pounds-per-hour, though overall fuel consumption rate for ground operations can be up to 1,500 pounds-per-hour per engine depending upon temperature, field elevation, and power settings during taxi and engine run-ups (T.O. 1F-16CM-1-1 2007, B4-1). Conservative FF_{ground} planning rates for the F-16 and F-15E are 1,500 pounds-per-hour and 3,000 pounds-per-hour, respectively. Time spent during ground operations, $t_{ground\ ops}$, varies depending upon aircrew efficiency, ground crew efficiency, taxi distances, and hold times. Though special "scramble" procedures exist to complete ground operations within only a few minutes under special controlled circumstances, typical fighter ground operations for combat missions last approximately 45 to 60 minutes. Conservatively assuming one hour of ground operations prior to takeoff at 1,500 pounds-per-hour per engine, $Q_{ground\ ops}$ for an F-16 is typically 1,500 pounds (1,500 pounds/hour x 1.0 hour) or less, and $Q_{ground\ ops}$ for an F-15E is typically 3,000 pounds ([2 x 1,500 pounds/hour] x 1.0 hour) or less.

Aircraft performance charts provide Q_{climb} based upon an aircraft's drag index, throttle setting (afterburner or mil power), and final altitude (T.O. 1F-15E-1-1 2005, B4-7; T.O. 1F-16CM-1-1 2007, B4-4 to B4-6). Given these parameters, one may determine time, distance, and fuel quantity consumed during the climb phase of a mission. As an example, Q_{climb} for an F-15E climbing to 30,000 feet above mean sea level with a takeoff weight of 70,000 pounds and a drag index of 90 is 3,100 pounds including 800 pounds from brake release to lift-off and 2,300 pounds from lift-off to arrival at 30,000 feet mean sea level (T.O. 1F-15E-1-1 2005, B4-2).

$Q_{departure}$ can be determined using the following relationship:

$Q_{departure} = (D_{departure})(FF_{departure}) / v_{departure}$

where $D_{departure}$ = distance flown during departure

$FF_{departure}$ = mean fuel flow during departure

$v_{departure}$ = mean airspeed during departure

To maximize distance traveled with a given amount of fuel, a pilot should fly at "maximum range" airspeed, sometimes called "optimum cruise" airspeed. This airspeed ($v_{max\ range}$) and its associated fuel flow ($FF_{max\ range}$) can be predicted using aircraft performance charts given aircraft gross weight, drag index, and altitude (T.O. 1F-15E-1-1 2005, B5-5 to B5-55; T.O. 1F-16CM-1-1 2007, B5-8 to B5-57). When maximizing distance flown for a given quantity of fuel during departure, $v_{departure} = v_{max\ range}$ and $FF_{departure} = FF_{max\ range}$; therefore,

$Q_{departure\ (min)} = (D_{departure})(FF_{max\ range}) / v_{max\ range}$

where $Q_{departure\ (min)}$ = minimum fuel consumption during departure

$FF_{max\ range}$ = fuel flow achieved at maximum range airspeed

$v_{max\ range}$ = maximum range airspeed

For example, a bomb-loaded F-16C weighing 32,000 pounds with a drag index of 150 flying a departure distance of 150 nautical mile at maximum range airspeed (456 knots) consumes approximately 1,250 pounds of fuel during departure: $Q_{departure} = (150$ $nm\ x\ 3783\ lb/hr) / (456\ nm/hr) = 1244\ lbs$ (T.O. 1F-16CM-1-1 2007, B5-44).

One can calculate $Q_{recovery}$ using the same logic as $Q_{departure}$:

$$Q_{recovery} = (D_{recovery})(FF_{recovery}) / v_{recovery}$$

where $D_{recovery}$ = distance flown during recovery

$FF_{recovery}$ = mean fuel flow during recovery

$v_{recovery}$ = mean airspeed during recovery

$FF_{max\ range}$) to consume the minimum amount of fuel per distance traveled. Therefore,

$$Q_{recovery\ (min)} = (D_{recovery})(FF_{max\ range}) / v_{max\ range}$$

where $Q_{recovery\ (min)}$ = minimum fuel consumption during recovery

$Q_{reserve}$, the fuel quantity reserved for divert to an alternate airfield if required, is dictated by regulation and varies depending upon the scenario. For USAF aircraft, "the PIC [pilot in command] must ensure the aircraft is carrying enough usable fuel on each flight to increase the total planned flight time between refueling points by 10 percent (up to a maximum of 45 minutes for fixed wing or 30 minutes for helicopters) or 20 minutes, whichever is greater." The instruction also states, "To compute fuel reserves . . . for turbine-powered aircraft, use fuel consumption rates that provide maximum endurance at 10,000 ft. Mean Sea Level" (AFI 11-202v3 2006, 11). In most F-15E and F-16 combat scenarios, one or more alternate landing fields or air refueling sources exist within a 20-minute flight (approximately 100 nautical miles), allowing use of the "20-minute rule." When such conditions exist, $Q_{reserve}$ for a combat-configured F-15E is 2,400 pounds

assuming a 7,000 pounds-per-hour max endurance fuel flow, and $Q_{reserve}$ for a combat-configured F-16C is 1,200 pounds assuming a 3,500 pounds-per-hour max endurance fuel flow. However, fuel reserve requirements in a remote location could be more than twice these quantities and must be calculated for each specific scenario.

With $Q_{on\text{-}station}$ broken into predictable values, the equation to calculate $t_{on\ station}$ becomes:

$$t_{on\text{-}station} = (Q_{total} - Q_{ground\ ops} - Q_{climb} - Q_{departure} - Q_{recovery} - Q_{reserve}) / FF_{on\text{-}station}$$

$FF_{on\text{-}station}$ is very difficult to predict accurately for a combat scenario. As defined earlier, $FF_{on\text{-}station}$ is the mean fuel flow during on-station operations, which includes on-station loitering and attacks. If one knows what portion of on-station time includes loiter and attack, $FF_{on\text{-}station}$ can be determined using standard methodology to calculate an arithmetic mean:

$$FF_{on\text{-}station} = [(t_{loiter})(FF_{loiter}) + (t_{attack})(FF_{attack})] / (t_{loiter} + t_{attack})$$

where t_{loiter} = on-station loiter time

FF_{loiter} = mean fuel flow during on-station loitering

t_{attack} = attack time

FF_{attack} = mean fuel flow during attack

However, t_{loiter} and t_{attack} are difficult to predict in a dynamic targeting application since targets and their associated distances have yet to emerge. Planners can either assume an

overall $FF_{on\text{-}station}$ value or assume separate values for t_{loiter}, FF_{loiter}, t_{attack}, and FF_{attack} values to calculate $FF_{on\text{-}station}$.

Values for t_{attack} and FF_{attack} can vary greatly. Regarding fuel conservation, the best-case scenario is a short duration attack, delivering guided weapons from high altitude in a low-threat environment. Such a scenario would require minimal deviation from $v_{max\ endure}$ and thus minimal use of fuel that could be used to extend persistence after the attack. The worst-case scenario is a lengthy, low altitude attack requiring high power settings for threat avoidance and unguided weapons delivery. Such a profile would consume the maximum amount of fuel that the pilot could have used to extend the persistence period.

To maximize loiter time with a given amount of fuel, a pilot should fly at "maximum endurance" airspeed ($v_{max\ endure}$), which along with its associated fuel flow ($FF_{max\ endure}$) can be predicted using aircraft performance charts given aircraft gross weight, drag index, and altitude (T.O. 1F-15E-1-1 2005, B6-5; T.O. 1F-16CM-1-1 2007, B5-8 to B5-57). When maximizing loiter time with a given quantity of fuel, $FF_{loiter} = FF_{max\ endure}$. Revising the formula for on-station fuel flow using $FF_{max\ endure}$, the minimum achievable fuel flow rate during on-station operations is:

$$FF_{on\text{-}station\ (min)} = [(t_{loiter})(FF_{max\ endure}) + (t_{attack})(FF_{attack})] / (t_{loiter} + t_{attack}).$$

where $FF_{on\text{-}station\ (min)}$ = minimum achievable fuel flow rate during on-station ops

$FF_{max\ endure}$ = fuel flow achieved at maximum endurance airspeed

For example, a planner can use this formula to predict the minimum potential on-station fuel flow rate for an F-15E that he or she assumes to remain on-station for a total of 4.0 hours including 1.0 hour of attack time. The attack scenario includes medium altitude ingress, a GBU-12 laser-guided bomb delivery, a GBU-38 JDAM delivery, and a medium altitude egress with some anticipated surface-to-air threat avoidance maneuvering. Using aircraft performance data, the planner predicts fuel flow rates of 8,000 pounds-per-hour for max endurance loitering and 12,000 pounds-per-hour for the expected attack profile. $FF_{on\text{-}station\ (min)}$ = [(3.0 hrs)(8,000 lb/hr) + (1.0 hrs)(12,000 lb/hr)] / (4.0 hrs) = 9000 pounds-per-hour. For fuel flow rate prediction, note that accurately assuming total on-station time is less important than accurately assuming the proportion of low-consumption loiter time to high-consumption attack time. If the mission above was actually 8.0 hours instead of 4.0 hours, and the attack time was 2.0 hours at 12,000 pounds-per-hour instead of 1.0 hours, the minimum achievable on-station fuel flow rate would remain 9,000 pounds-per-hour.

As demonstrated in the preceding paragraphs, a pilot can maximize on-station time by flying the departure and recovery phases of a mission at maximum range airspeed ($v_{max\ range}$) and by loitering at maximum endurance airspeed ($v_{max\ endure}$). If procedures dictate that aircrews execute dynamic targeting missions using these fuel-saving procedures, one can predict maximum $t_{on\text{-}station}$ as follows:

$$t_{on\text{-}station\ (max)} =$$
$$(Q_{total} - Q_{ground\ ops} - Q_{climb} - Q_{departure\ (min)} - Q_{recovery\ (min)} - Q_{reserve}) / FF_{on\text{-}station\ (min)}$$

To achieve the final form of this equation, replace $Q_{departure\,(min)}$ and $Q_{recovery\,(min)}$ with previously identified formulas that contain predictable values. The resulting equation enables one to predict the maximum time that an aircraft can provide dynamic targeting persistence given a limited amount of fuel:

$$t_{on\text{-}station\,(max)} = (Q_{total} - Q_{ground\,ops} - Q_{climb} - [(D_{departure})(FF_{max\,range}) / v_{max\,range}] -$$

$$[(D_{recovery})(FF_{max\,range}) / v_{max\,range}] - Q_{reserve}) / FF_{on\text{-}station\,(min)}$$

Measuring Maximum Potential Engagement Area

The geographic surface area potentially vulnerable to dynamic targeting is a function of the number of aircraft, the combat radius of each aircraft, and the positioning of those aircraft. For each aircraft, one can calculate the potential geographic area vulnerable to attack using the area formula for a circle:

$$A = \Pi R^2$$

where A = *vulnerable area*

$\quad$ R = *combat radius*

The difficulty associated with accurately defining and calculating combat radius complicates practical application of the above formula. JP 1-02 defines combat radius, also called radius of action, as "the maximum distance a ship, an aircraft, or a vehicle can travel away from its base along a given course with normal combat load and return without refueling, allowing for all safety and operating factors" (JP 1-02 2007, 444). Applying the definition for combat radius to the above formula, the area potentially

vulnerable to attack by a given aircraft equals circular area (*A*) around that aircraft's

departure runway location. However, the JP 1-02 definition does not directly account for

the enhancement in aircraft range that air refueling provides.

To account for enhanced range capability associated with air refueling, this

analysis introduces the term *instantaneous combat radius (R $_{inst}$)*, defined as "the

maximum distance an aircraft can travel at its current fuel state along a given course with

normal combat load and return to its refueling source with appropriate recovery fuel."

Refueling sources may include both ground and air refueling sources, and recovery fuel

includes fuel necessary to return to the intended landing base of landing with appropriate

fuel reserves as dictated by regulation. The depiction in figure 10 represents the

relationship between instantaneous combat radius and area vulnerable to attack.

The instantaneous combat radius around an aircraft defines the area vulnerable to

an attack by that aircraft:

$$A_{inst} = \Pi (R_{inst})^2$$

where A_{inst} = *instantaneous vulnerable area*

R_{inst} = *instantaneous combat radius*
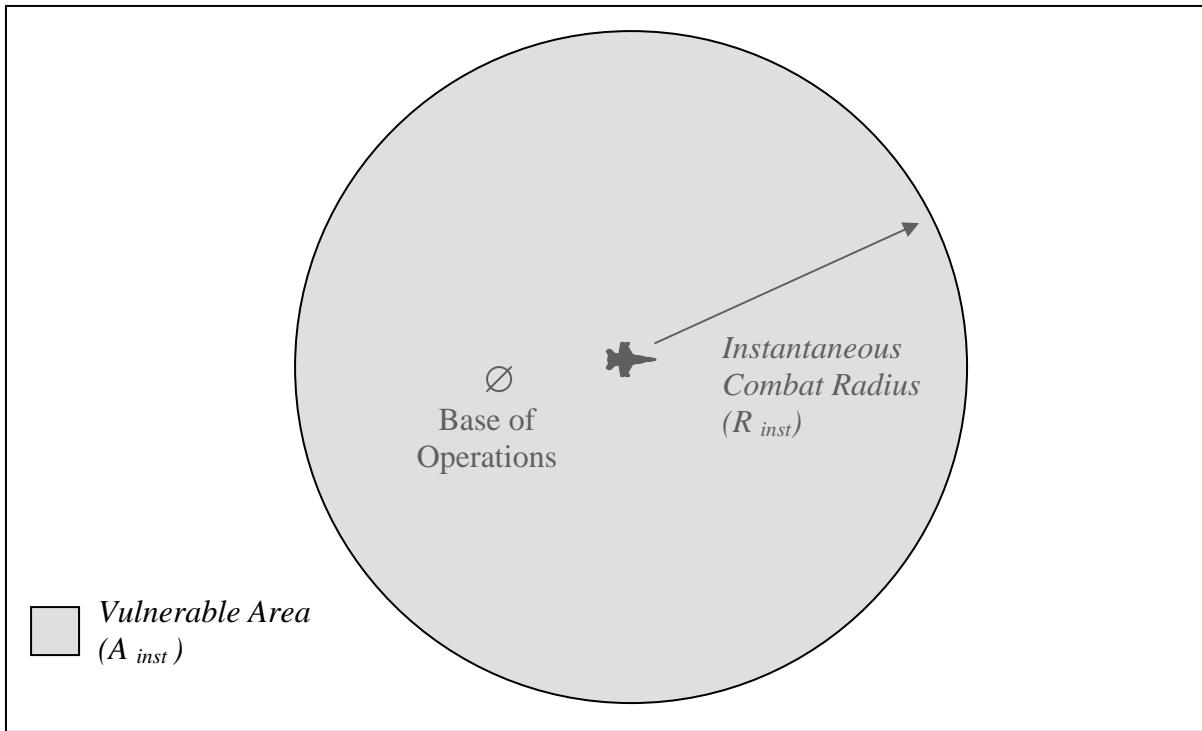
Figure 10. Relationship of Instantaneous Combat Radius to Vulnerable Area

A planner can predict an aircraft's maximum range potential by using the relationships between anticipated airspeed, fuel quantity, and fuel flow. One-half of the distance value provides the radius from a given point:

$R_{inst} = 0.5 (v_{mean})(Q_{current} - Q_{recovery} - Q_{reserve}) / (FF_{mean})$

where v_{mean} = *mean airspeed*

$Q_{current}$ = *current fuel quantity*

$Q_{recovery}$ = *fuel quantity consumed during recovery (station exit to landing)*

$Q_{reserve}$ = *fuel quantity reserved for divert to an alternate airfield if required*

FF_{mean} = *mean fuel flow*

Pilots can achieve optimum instantaneous combat radius at any given aircraft fuel state by operating at maximum range airspeed, which provides the greatest distance for a given fuel quantity. Optimizing variables for maximum range operations ($v_{mean} = v_{max\ range}$, and $FF_{mean} = FF_{max\ range}$) provides the largest potential instantaneous combat radius for an aircraft's current fuel state:

$$(R_{inst})_{opt} = 0.5\ (v_{max\ range})(\ Q_{current} - Q_{recovery} - Q_{reserve})\ /\ (FF_{max\ range})$$

where $(R_{inst})_{opt}$ = *optimum instantaneous combat radius*

Finally, one can calculate the maximum area vulnerable to dynamic targeting at the current fuel state by applying optimum instantaneous combat radius to the basic area formula:

$$(A_{inst})_{opt} = \Pi\ [0.5\ (v_{max\ range})(\ Q_{current} - Q_{recovery} - Q_{reserve})\ /\ (FF_{max\ range})]^{\ 2}$$

where $(A_{inst})_{opt}$ = *optimum instantaneous vulnerable area*

Replacing Π with the value *3.14* for practical application, the final form of the formula to calculate the maximum potential area vulnerable to an aircraft's dynamic targeting attack at a given fuel state is:

$$(A_{inst})_{opt} = 3.14\ [0.5\ (v_{max\ range})(\ Q_{current} - Q_{recovery} - Q_{reserve})\ /\ (FF_{max\ range})]^{\ 2}$$

An aircraft achieves its maximum instantaneous combat radius potential for a given fuel tank configuration immediately after air refueling to its maximum capacity

($Q_{current} = Q_{capacity}$). At that instant, the optimum instantaneous vulnerable area is also at maximum potential as demonstrated by the following relationship:

$$(A_{inst})_{max} = 3.14 \ [0.5 \ (v_{max \ range})(\ Q_{capacity} - Q_{recovery} - Q_{reserve}) \ / \ (FF_{max \ range})] ^ 2$$

where $(A_{inst})_{max}$ = *maximum instantaneous vulnerable area*

$Q_{capacity}$ = *maximum aircraft fuel capacity*

Importantly, planners must realize that the above formula is a *comparative* tool to calculate the maximum theoretical area that an aircraft could access on a direct, non-maneuvering flight path at optimum altitude and maximum range airspeed. Additionally, unquantifiable variables such as enemy threats and adverse weather conditions influence an aircraft's ability to reach and effect targets. In order to use the above methodology as a *predictive* tool for tactical planning, one must apply values appropriate to the expected tactical scenario (higher fuel consumption rate, indirect flight path, and others).

Additionally, the entire accessible area around an aircraft often does not contain potential targets. A few scenarios such as counterinsurgency air missions staged from central Iraq provide target potential in all directions from the point that an aircraft completes air refueling. However, in many scenarios only a portion of the accessible area contains potential targets because vulnerable air refueling aircraft typically orbit outside of hostile airspace if any air-to-air or surface-to-air threat exists (see figure 11). Planners must determine what portion of accessible airspace is over terrain containing potential targets and adjust vulnerable area comparisons accordingly. Sample problems presented

later in this chapter provide examples of calculating reduced portions of the maximum

potential vulnerable area appropriate for a given scenario.
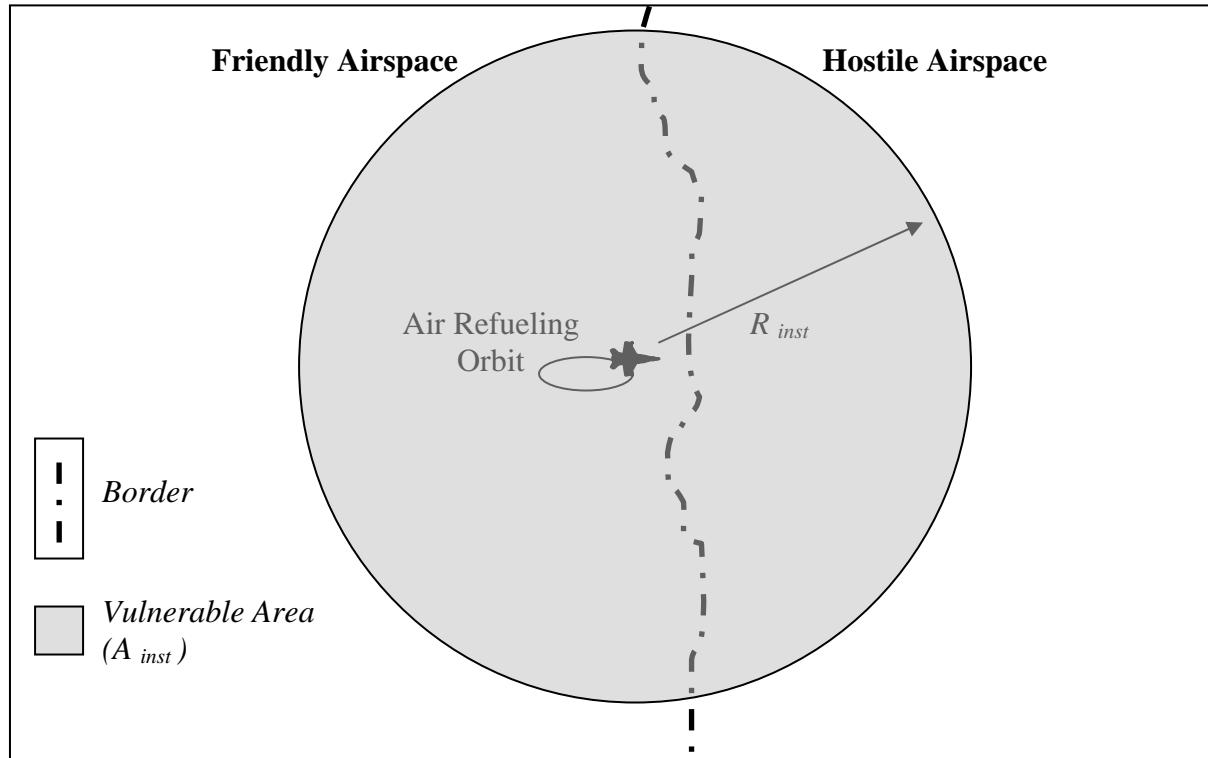
Figure 11. Vulnerable Area Outside Hostile Airspace

Combining Area and Time Persistence Measurements

Calculating the maximum area vulnerable to attack is beneficial, but an aircraft's

on-station time includes many periods during which maximum area cannot be achieved

due to fuel limitations. An aircraft can only achieve its maximum combat radius,

$(R_{inst})_{max}$, and maximum potential vulnerability area, $(A_{inst})_{max}$, for the period during

which air-received fuel remains available to fill the fighter's tanks to maximum capacity

$(Q_{current} = Q_{capacity})$. After that time, the optimum instantaneous combat radius gradually

decreases in proportion to the quantity fuel on board. A thorough comparison of maximum area coverage during an on-station period must not only include each aircraft's maximum capability but also the reduced persistence after air refueling is no longer available. Figure 12 provides a graphic representation of the area-time relationship that accounts for reduced combat radius after an aircraft can no longer receive a maximum fuel load:
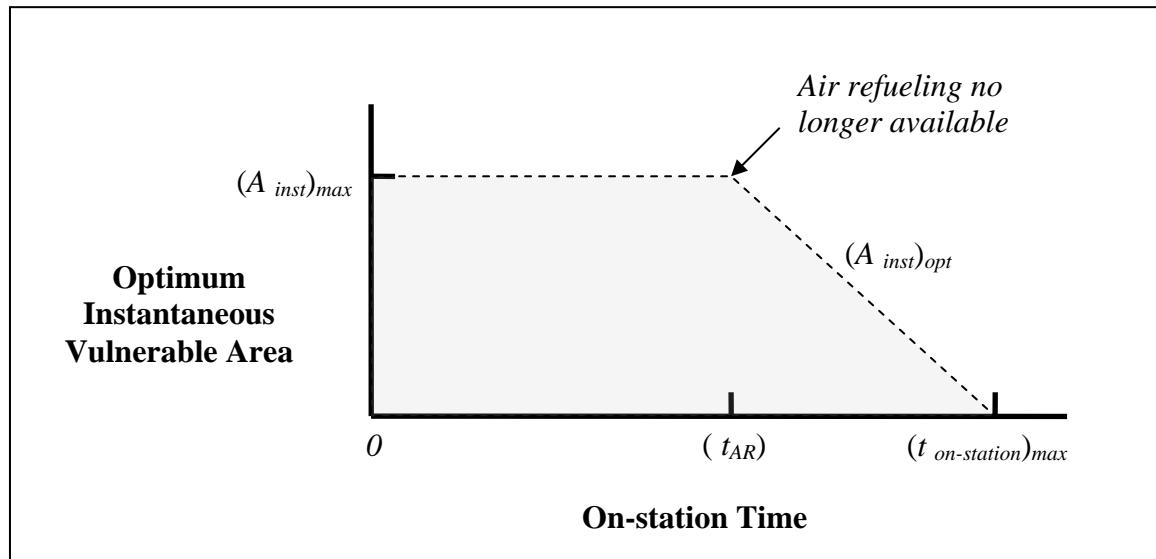
Figure 12. Optimum Instantaneous Vulnerable Area during On-Station Time, Single Aircraft with Air Refueling Available

The newly introduced value in this figure, t_{AR}, is the time from on-station arrival to air refueling non-availability. One can estimate the maximum time to t_{AR} for an aircraft by determining the air refueling quantity available after replenishing ground, climb, and departure fuel, then reducing that quantity at a rate equal to the max endurance fuel flow, $FF_{max\ endure}$.

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$$t_{AR} = (Q_{\text{air refuel}} - Q_{\text{ground}} - Q_{\text{climb}} - Q_{\text{departure}}) / FF_{\text{max endure}}$$

where t_{AR} = time from on-station arrival to air refueling non-availability

$Q_{\text{air refuel}}$ = total quantity of fuel available per aircraft via air refueling

If air refueling is not available after arrival on-station, then $t_{AR} = 0$ and the instantaneous vulnerable area immediately begins to decrease as the aircraft's fuel is depleted from its own tanks (see figure 13). Additionally, the initial instantaneous vulnerable area is less than the maximum potential vulnerable area when air refueling is not available because an air refueler is not available to fill the attack aircraft's fuel tanks prior to a strike.
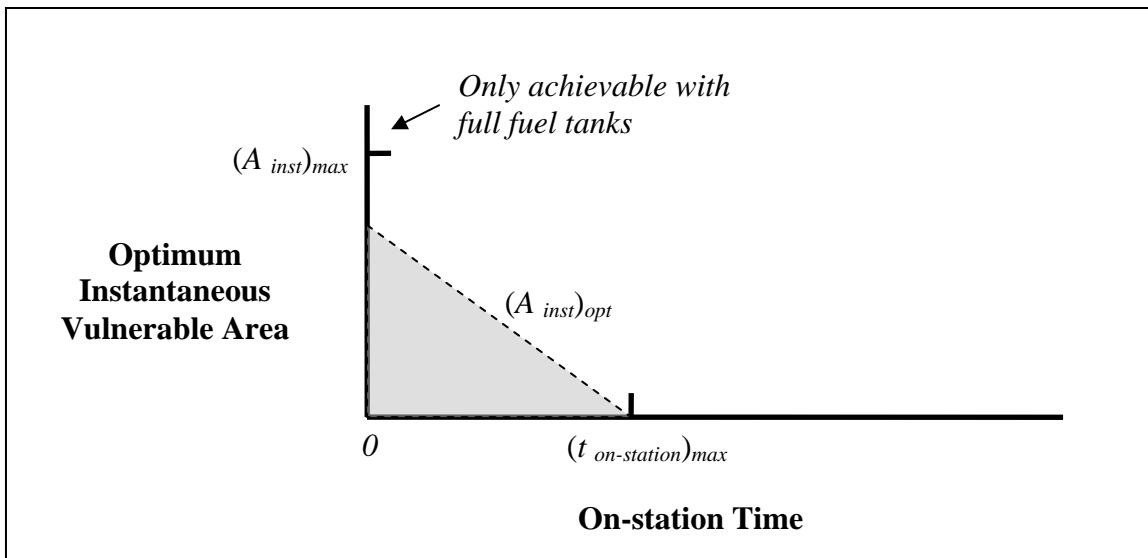

Figure 13. Optimum Instantaneous Vulnerable Area during On-Station Time, Single Aircraft without Air Refueling Available

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Rather than separately analyzing area and time coverage capabilities of an aircraft, a planner can simultaneously consider both area and time dimensions of persistence by calculating the sum total of optimum instantaneous vulnerable area for the aircraft's total on-station period. The shaded area on the charts in figures 12 and 13 represents total area-time persistence, $P_{area\text{-}time}$, enabling a single-value comparison that considers both area and time components of persistence. The following formula allows a planner to quantify area-time persistence for a given period:

$P_{area\text{-}time} = \sum(A_{inst})_{opt}$ *from t=0 to t=(t $_{on\text{-}station}$)$_{max}$*

where $P_{area\text{-}time}$ = *total area-time persistence during an on-station period*

For a single aircraft with no air refueling available, as represented in figure 13, the graphic area is shaped as a triangle. For a single aircraft with air refueling available, as represented in figure 12, it is shaped as a rectangle from [$t=0$] to [$t=t_{AR}$] and a triangle from [$t=t_{AR}$] to [$t=(t_{on\text{-}station})_{max}$]. The following equation calculates a total area-time persistence value for a single aircraft by summing the instantaneous vulnerable area values for the entire on-station period:

$P_{area\text{-}time} = \sum(A_{inst})_{opt}$ from [$t=0$] to [$t=(t_{on\text{-}station})_{max}$]

$= \sum(A_{inst})_{opt}$ from [$t=0$] to [$t=t_{AR}$] $+ \sum(A_{inst})_{opt}$ from [$t=t_{AR}$] to [$t=(t_{on\text{-}station})_{max}$]

$= [(A_{inst})_{max}][t_{AR}] + \frac{1}{2}[(A_{inst})_{opt}$ at $t= t_{AR}][(t_{on\text{-}station})_{max} - t_{AR}]$

where t_{AR} = *time from on-station arrival to air refueling non-availability*

If sufficient air refueling is available to fill an aircraft's tanks to maximum capacity after arrival on-station, then $[(A_{inst})_{opt}$ at $t = t_{AR}]$ is equal to $(A_{inst})_{max}$ as shown in figure 12. If sufficient air refueling is not available to fill the tanks, then $[(A_{inst})_{opt}$ at $t = t_{AR}]$ is equal to $(A_{inst})_{opt}$ upon arrival on-station $(t = t_{AR} = 0)$ as shown in figure 13. The final form of the equation that quantifies maximum potential area-time persistence for a single aircraft is:

$$(P_{area\text{-}time})_{max} = [(A_{inst})_{max}][t_{AR}] + 0.5\ [(A_{inst})_{opt}\ \text{at}\ t = t_{AR}][(t_{on\text{-}station})_{max} - t_{AR}]$$

In practical applications, one can plot instantaneous vulnerable area versus on-station time by tabulating area and time data in an automated spreadsheet program and charting the results. Most such programs also provide a function to sum the graphic area, providing a relatively easy means to achieve $(P_{area\text{-}time})_{max}$ after entering the appropriate persistence variables for a given scenario. This is a particularly useful technique when the resulting plot for $(A_{inst})_{opt}$ is non-linear.

The following example applies the methodology presented above to predict the maximum potential area-time persistence value for a notional aircraft. Assume that an aircraft can potentially access a maximum instantaneous area of 100,000 square nautical miles from its on-station location after all tanks are full. Sufficient fuel is available to "top off" via air refueling for a period of 2.0 hours, after which the aircraft holds enough self-contained fuel to remain on station for an additional 1.5 hours at maximum endurance fuel flow.

$(P_{area\text{-}time})_{max} = [100,000\ nm^2][2.0\ \text{hrs}] + 0.5\ [100,000\ nm^2][3.5\ hrs - 2.0\ hrs]$

$= 275,000\ nm^2\text{-}hrs.$

Now assume that another aircraft can only access 80,000 square nautical miles from its on-station location after all tanks are full. However, a lower fuel consumption rate and the same amount of on-station fuel extends the maximum refueling availability period to 2.5 hours, after which the aircraft can remain on station for an additional 2.0 hours at maximum endurance fuel flow. Its maximum potential area-time persistence value is:

$(P_{area-time})_{max} = [80,000 \text{ nm}^2][2.5 \text{ hrs}] + 0.5 [80,000 \text{ nm}^2][4.5 \text{ hrs} - 2.5 \text{ hrs}]$

$= 320,000 \text{ nm}^2\text{-hrs.}$

Though the aircraft in the first example possesses exclusive capability to access distant areas with its greater combat radius, the aircraft in the second example provides greater area-time persistence over the terrain that it can access. Of course, the area-time persistence value does not consider effects capabilities, discussed in a later section.

<center>Measuring Area-Time Persistence for a Force
Containing Multiple Aircraft</center>

Measuring the total area-time persistence capability of an attack force containing multiple aircraft requires significant additional analysis. A planner cannot simply add the single-aircraft persistence value, *(P_{area-time})_{max}*, for each aircraft in the attack force because simultaneous presence may provide both area and time overlaps (see figure 14).

At any given instant, a potential target is not made "more vulnerable" by the added presence of multiple strike assets--it is either vulnerable or it is not. For example, the area-time persistence of a single F-15E is equivalent to that of flight of two similarly-configured F-15Es originating from the same refueling source for the same on-station period because maximum instantaneous area, *(A_{inst})_{max}*, and maximum on-station time,

$t_{\text{on-station (max)}}$, does not increase for the force of two aircraft. Of course, presence of multiple aircraft allows continuous persistence against potential targets if one aircraft is engaging a target, an important consideration discussed later. However, if two aircraft maintain separate on-station locations then the area component of persistence is increased. Similarly, if the two aircraft maintain non-simultaneous on-station periods then the time component of persistence is increased
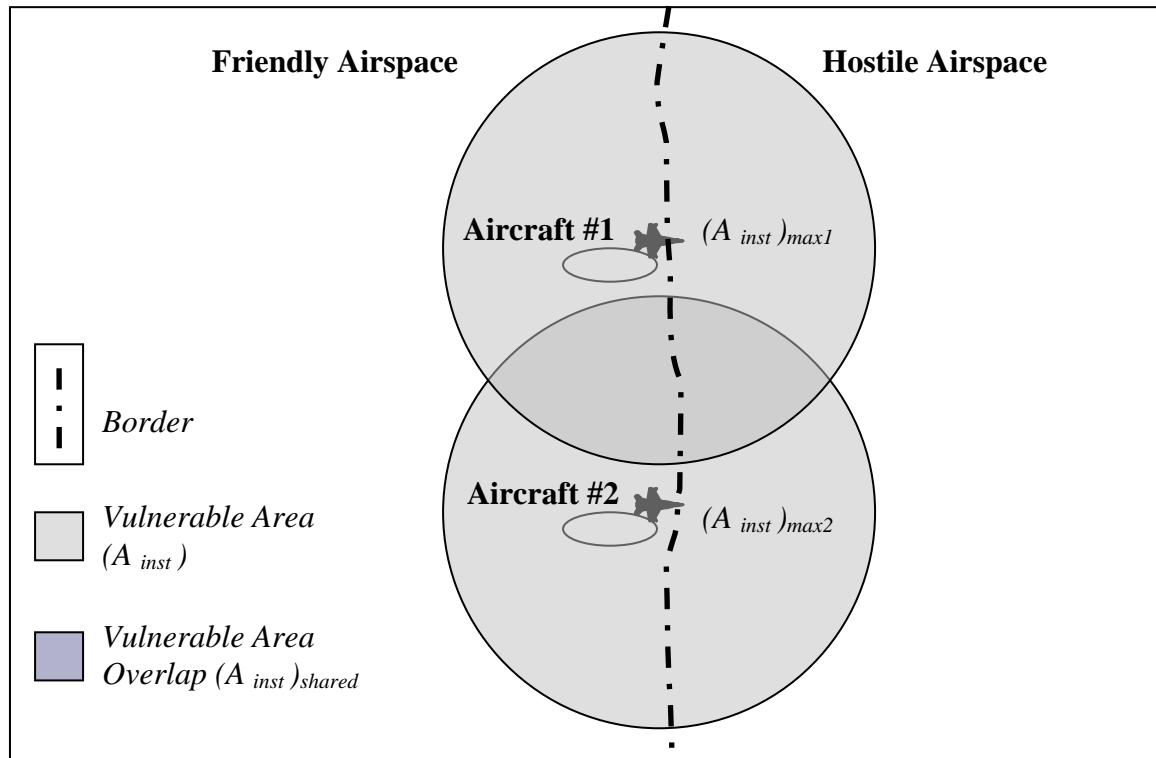

Figure 14. Vulnerable Area Overlap

The total instantaneous area vulnerable to attack from a force of multiple aircraft is attained by calculating (A_{inst}) for one aircraft and adding only those areas exclusively accessible by other aircraft within the same force:

$$Force\ (A\ _{inst}) = (A\ _{inst})_1 + [(A\ _{inst})_2 - (A\ _{inst})_{shared}]...+ [(A\ _{inst})_n - (A\ _{inst})_{shared}]$$

where   *Force (A $_{inst}$) = attack force total instantaneous vulnerable area*

$(A\ _{inst})_n$ = *instantaneous vulnerable area for* n^{th} *aircraft*

$(A\ _{inst})_{shared}$ = *portion of vulnerable area also made vulnerable by other aircraft*

For example, assume that planners wish to know the potential enemy terrain that a force of two aircraft can hold vulnerable to dynamic targeting. The aircraft will operate autonomously from two separate on-station locations similar to the arrangement shown in figure 14. Air refueling is available at both on-station orbits, and each aircraft can achieve a maximum instantaneous vulnerable area of 120,000 square nautical miles from their respective on-station locations with full fuel tanks. Approximately 25 percent of the area accessible by aircraft #1 overlaps the area accessible by aircraft #2. The planner can predict the maximum total area that is vulnerable to attack by either aircraft in the given scenario as follows:

Force (A $_{inst}$) = (A $_{inst}$)$_1$ + [(A $_{inst}$)$_2$ − (A $_{inst}$) $_{shared}$]

$=120,000\ nm^2 + [120,000\ nm^2 − 0.25(120,000\ nm^2)]$

$= 210,000\ nm^2$

In addition, since approximately 50 percent of the vulnerable area in this scenario includes friendly terrain (see figure 14), one should adjust the value to include only the maximum vulnerable hostile area, which only includes terrain containing potential targets:

Hostile (A $_{inst}$)$_{max}$ = 0.50 (210,000 nm^2)

= 105,000 nm^2

Now assume that the same planner must calculate the maximum vulnerable area
after increasing the force size to four aircraft (two flights of two aircraft) operating from
the same on-station locations. Though the additional aircraft provide potential to attack
more targets and to attack targets simultaneously, they do *not* increase vulnerable area
because *(A $_{inst}$)* for each wingman overlaps that of the flight lead in close proximity. In
other words, 100 percent of *(A $_{inst}$)$_2$* and *(A $_{inst}$)$_4$* are shared by other aircraft.

Force (A $_{inst}$) = (A $_{inst}$)$_1$ + [(A $_{inst}$)$_2$ − (A $_{inst}$) $_{shared}$] + [(A $_{inst}$)$_3$ − (A $_{inst}$) $_{shared}$] + [(A $_{inst}$)$_4$ −

(A $_{inst}$) $_{shared}$]

= 120,000 nm^2 + [120,000 nm^2 − 1.00(120,000 nm^2)] + [120,000 nm^2 −

0.25(120,000 nm^2)] + [120,000 nm^2 − 1.00(120,000 nm^2)]

= 210,000 nm^2

Vulnerable Hostile Area = 0.50 (210,000 nm^2) = 105,000 nm^2

As evidenced within the equation for *Force (A $_{inst}$)*, a planner can maximize
vulnerable area by eliminating individual aircraft coverage overlaps *((A $_{inst}$) $_{shared}$ = 0)*.
However, such an arrayal of aircraft would also eliminate the benefits provided by
multiple aircraft presence, which includes:

1. Potential to deliver more effects per given area

2. Continuous maximum persistence while an aircraft is engaged

3. Effects redundancy if an aircraft is rendered ineffective

4. Ability to disperse aircraft closer to potential time-sensitive target areas

Additionally, scarce availability of refueling aircraft limits the number of on-station locations with co-located air refueling tracks. Experienced air component commanders understand force placement risks and rewards, but appropriate presentation of persistence information can make the best option more apparent.

As with determining force maximum instantaneous area, calculating potential time on-station for a multi-aircraft force requires consideration of overlapping presence. A planner may predict a force's maximum time on-station by calculating $t_{\text{on-station (max)}}$ for one aircraft and adding only those periods during which other aircraft in the same force provide exclusive presence.

$$\text{Force } t_{\text{on-station (max)}} = t_{\text{on-station (max)1}} + [t_{\text{on-station (max)2}} - t_{\text{on-station (max) shared}}]... +$$

$$[t_{\text{on-station (max) } n} - t_{\text{on-station (max) shared}}]$$

where $\text{Force } t_{\text{on-station (max)}} = \text{attack force maximum time on-station}$

$t_{\text{on-station (max) } n} = \text{maximum time on-station for } n^{th} \text{ aircraft}$

For instance, if two aircraft have a maximum on-station time capability of four hours each, and the second aircraft arrives on-station two hours after the first, then the maximum time on-station time for the two-ship force is six hours:

$\text{Force } t_{\text{on-station (max)}} = t_{\text{on-station (max)1}} + [t_{\text{on-station (max)2}} - t_{\text{on-station (max) shared}}]$

$= 4.0 \text{ hrs} + [4.0 \text{ hrs} - 2.0 \text{ hrs}]$

$= 6.0 \text{ hrs}$

Assuming that the force size increases to four aircraft of the same type, with a flight of two aircraft arriving two hours after the first, then the force's maximum on-station time does not increase because of simultaneous time coverage:

Force t $_{on\text{-}station\,(max)}$ = t $_{on\text{-}station\,(max)1}$ + [t $_{on\text{-}station\,(max)2}$ − t $_{on\text{-}station\,(max)\,shared}$]...+

[t $_{on\text{-}station\,(max)\,n}$ − t $_{on\text{-}station\,(max)\,shared}$]

= 4.0 hrs + [4.0 hrs − 4.0 hrs] + [4.0 hrs − 2.0 hrs] + [4.0 hrs − 4.0 hrs]

= 6.0 hrs

Intuitively, a force planner can maximize an attack force's total on-station time by eliminating time overlaps among aircraft (*t $_{on\text{-}station\,(max)\,shared}$ = 0*). However, the risks associated with sacrificing redundancy for efficiency are identical to those presented in the area coverage analysis.

With overlaps considered in both maximum instantaneous area and on-station time calculations for a multi-aircraft force, a planner can provide an area-time persistence value using the single-aircraft area-time persistence equation presented previously:

Force P$_{area\text{-}time}$ = $\sum$ Force A $_{inst}$ from t=0 to t=(t $_{on\text{-}station}$)$_{max}$

where *Force P$_{area\text{-}time}$ = attack force area-time persistence during an on-station period*

Of course, summing the area coverage values becomes more difficult because the force's persistence capability changes not only with air refueling availability, but also with aircraft arrivals at and departures from separate on-station locations. Figure 15 represents a notional force's area-time persistence if operating from two on-station locations as depicted in figure 14 with staggered aircraft on-station times. The shaded areas

demonstrate area-time persistence relationships among aircraft, and the sum of the shaded areas represents the force's total area-time persistence.
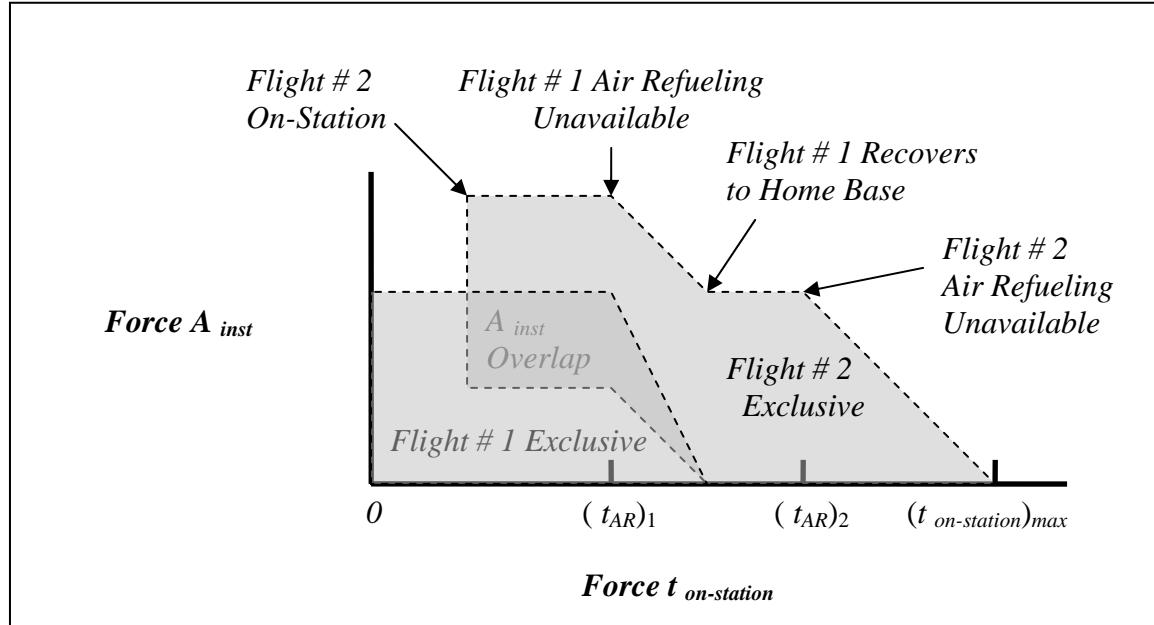
Figure 15. Area-Time Persistence Chart, Two Flights of Aircraft with
Air Refueling Available

To illustrate an area-time persistence calculation for multiple aircraft, assume that a force includes two flights containing two aircraft each. All aircraft are of the same type, possess the same fuel tank configuration, and depart and recover in pairs. The maximum instantaneous combat radius, $(R_{inst})_{max}$, is 200 nautical miles for each aircraft. The flights operate from two separate on-station locations that are 100 nautical miles apart and potential targets exist in all directions up to distances exceeding 200 nautical miles. Air refueling is available at each on-station location for 1.5 hours and each aircraft has

sufficient self-contained fuel to remain on-station for an additional 30 minutes before

recovering to home base. Figure 16 shows a sample map overlay for this scenario.
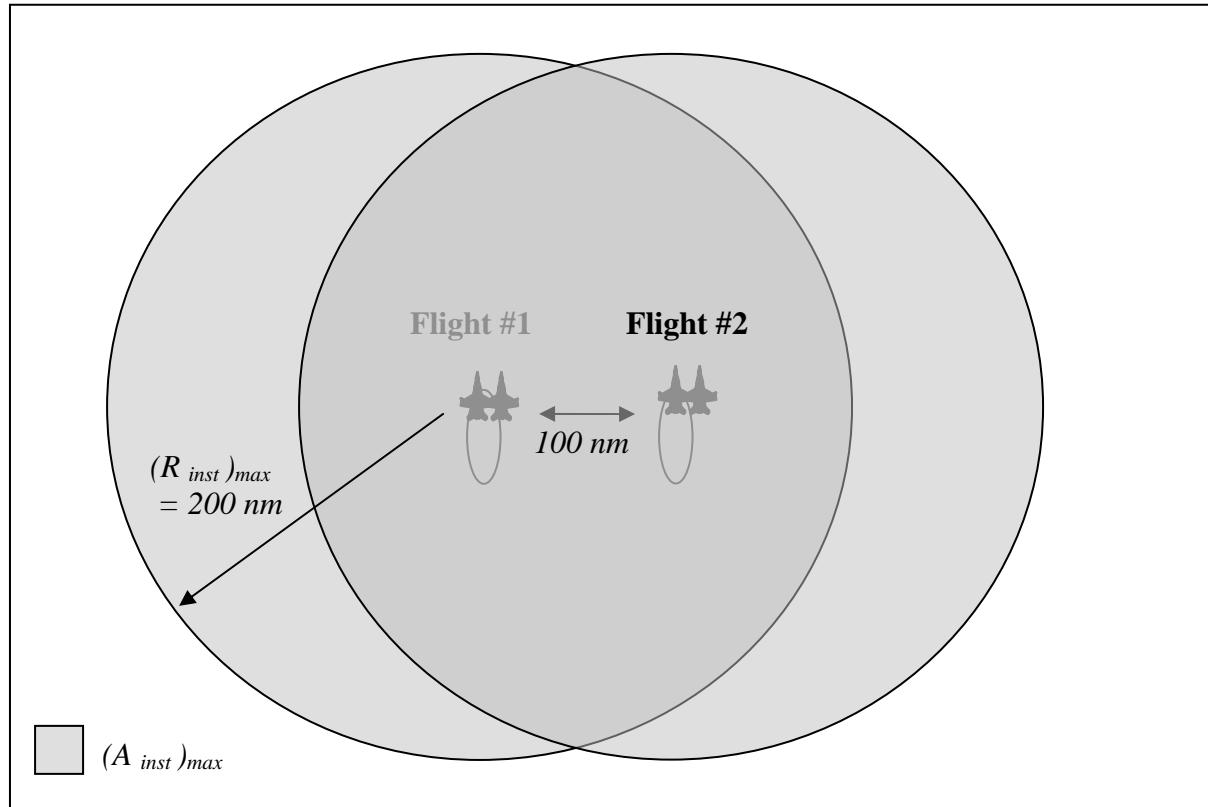
Figure 16. Map Overlay for Sample Area-Time Persistence Calculation

The area-time persistence value is calculated by summing *Force (A $_{inst})_{max}$* values

for force's entire time on-station. Since not all aircraft are present during the entire

period, this process requires calculation of maximum instantaneous vulnerable area for

individual aircraft, for the separate flights of aircraft, and for the entire force.

Each aircraft's maximum instantaneous vulnerable area is calculated using the

area formula:

$(A_{inst})_{max} = 3.14 [(R_{inst})_{max}]^2$

$= 3.14 \ (200 \ \text{nm})^2$

$= 196{,}250 \ \text{nm}^2$

Each flight's maximum instantaneous vulnerable area is equal to that of a single aircraft operating from the same on-station location $(196{,}250 \ \text{nm})^2$ because both aircraft within each two-ship flight have an identical maximum combat radius and originate from the same location.

The force's maximum instantaneous vulnerable area, *Force (A $_{inst}$)$_{max}$*, is represented by the sum of all shaded areas in figure 16. The following calculations account for the 100 percent overlap in flight lead and wingman maximum area coverage and the 60 percent overlap in maximum area coverage between both flights of aircraft:

Force (A $_{inst}$)$_{max}$ = (A $_{inst}$)$_1$ + [(A $_{inst}$)$_2$ − (A $_{inst}$) $_{shared}$] + [(A $_{inst}$)$_3$ − (A $_{inst}$) $_{shared}$] + [(A $_{inst}$)$_4$ − (A $_{inst}$) $_{shared}$]

$= 196{,}250 \ \text{nm}^2 + [196{,}250 \ \text{nm}^2 − 1.00(196{,}250 \ \text{nm}^2)] + [196{,}250 \ \text{nm}^2 −$

$0.60(196{,}250 \ \text{nm}^2)] + [196{,}250 \ \text{nm}^2 − 1.00(196{,}250 \ \text{nm}^2)]$

$= 314{,}000 \ \text{nm}^2$

This value requires no adjustment for friendly versus hostile area coverage since potential targets exist in all directions.

With a predicted maximum *Force (A $_{inst}$)$_{max}$* value and predicted *(A $_{inst}$)* values for each segment of the time on-station, a total area-time persistence value can be determined. Figure 17 provides the area-time persistence chart for this sample problem. The total shaded area on the chart represents the total area-time persistence for the entire force, calculated per the previously presented methodology:

Force P$_{area-time}$ = $\sum$ Force A $_{inst}$ from t=0 to t=(t $_{on\text{-}station}$)$_{max}$

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$$= A_{inst} [t=0 \text{ to } 1.0] + A_{inst} [t=1.0 \text{ to } 1.5] + A_{inst} [t=1.5 \text{ to } 2.0] + A_{inst} [t=2.0 \text{ to } 2.5]$$

$$+ A_{inst} [t=2.5 \text{ to } 3.0]$$

$$= (196{,}250 \text{ nm}^2)(1.0 \text{ hr}) + (314{,}000 \text{ nm}^2)(1.5 - 1.0 \text{ hrs}) + 0.5(314{,}000 + 196{,}250 \text{ nm}^2)(2.0$$

$$- 1.5 \text{ hrs}) + (196{,}250 \text{ nm}^2)(2.5 - 2.0 \text{ hrs}) + 0.5(196{,}250 \text{ nm}^2)(3.0 - 2.5 \text{ hrs})$$

$$= 628{,}000 \text{ nm}^2\text{-hr}$$
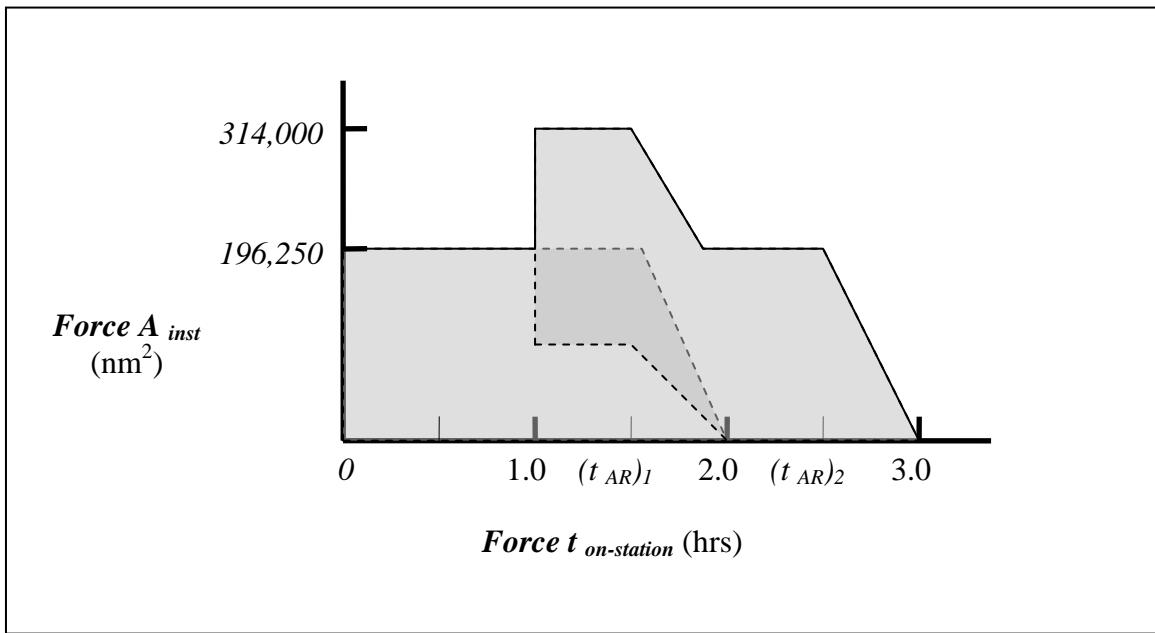
Figure 17. Area-Time Persistence Chart for Sample Problem

The area-time persistence value, $P_{area\text{-}time}$, provides a quantitative means to compare a force's persistence capability with that of another force in the same scenario. A planner can also use the area-time persistence chart to analyze redundancy of presence, indicated by the dark shaded portion in figure 17, and make on-station location or time adjustment recommendations to maximize efficiency.

Measuring Effects Persistence

An aircraft's ability to effect targets is the most difficult aspect of persistence to quantitatively measure. Since the persistence definition states that a force must not only be present, but also must be able to "provide desired effects," the overall measure of persistence must include the force's ability to provide the desired effects.

Effects may include both lethal and non-lethal targeting means. In order to limit scope, the following analysis addresses only lethal effects--"bombs and bullets." Non-lethal effects include activities such as electronic attack, reconnaissance, surveillance, and show of force. Even the mere presence of an attack force may provide non-lethal deterrence effects against an enemy that is aware of that presence and wishes to avoid the repercussions of a particular action--a notion that provides a strong argument for employing multiple aircraft even if they carry fewer bombs than a force containing fewer aircraft. The difficult measurement of such non-lethal effects potential requires separate analysis beyond the scope of this study.

Upon initial assessment, determining an aircraft's ability to provide lethal effects seems as easy as counting the number of bombs that the aircraft can carry and deliver. However, other variables complicate practical application: What types of munitions can the aircraft deliver? How many bombs or bullets are required to achieve the desired effects? This research makes broad comparisons between aircraft systems requiring broad assumptions to answer such questions. However, the reader should realize that, given scenario-specific requirements, planners could achieve a reasonably accurate quantitative assessment of one or more systems' ability to provide desired lethal effects.

This study proposes that one can quantify dynamic targeting effects potential by calculating and assigning a persistence value based upon the number of "DPI" (desired point of impact) locations that an aircraft can effect in a given weapons configuration. JP 1-02 defines DPI as "a precise point, associated with a target, and assigned as the center for a single unitary weapon to create a desired effect" (2007, 158). A single target may include multiple DPIs. For instance, a surface-to-air missile system, usually considered a single target, may include one or more DPIs for each of its sub-systems (radar antenna, missile launchers, and others). Additionally, planners may sometimes need to apply more than one bomb against a single point to account for delivery error and or to maximize area effects around that point. Of course, the advent of precision weaponry typically allows an aircrew to effect a single DPI with a single bomb.

Each aircraft tasked to a dynamic targeting mission has the potential to effect a finite number of DPIs depending upon the number and type of munitions being carried. By carefully analyzing the expected target types and tailoring the aircraft munitions load to maximize effects, a planner can calculate the maximum potential number of DPIs that each aircraft can effect.

For comparative use, this study will quantify effects persistence ($P_{effects}$) by calculating the *maximum* number of DPIs that each aircraft can appropriately effect in a given scenario:

($P_{effects}$)$_{max}$ = (max # of deliverable munitions) / (# of munitions required to achieve desired effect at a single DPI)

As stated concerning area-time persistence, this methodology measures *maximum* potential capability for comparative purposes. In order to predict the *expected* number of DPIs that an aircraft will effect, accounting for system malfunctions and operator error, planners must incorporate a factor to account for realistic tactical contingencies. One can determine such a factor using weapons effectiveness data not presented in this unclassified study.

As an example of determining *($P_{effects}$)$_{max}$* for a given scenario, assume that a planner expects dynamic targeting DPIs to be associated with unhardened facilities and similar structures that a single 500-pound precision weapon can destroy without excessive collateral damage. Destruction is the desired effect. F-16s are available for mission tasking, and each aircraft can deliver a maximum of four precision weapons of the required type. Each aircraft also has a 20-millimeter cannon and air-to-air missiles, but these weapons cannot achieve the desired effect on the expected DPI-types. The planner can predict the maximum DPI equivalent value for each F-16 as follows:

$(P_{effects})_{max}$ = (4 deliverable munitions) / (1 munition per DPI) = 4 DPIs

In other words, if the aircraft can maintain presence (area-time persistence) then it can achieve desired effects against a maximum of four DPIs (effects persistence).

Now assume that the planner expects the DPIs to be associated with dispersed, unarmored transport vehicles. The maximum DPI equivalent value would increase because pilots can also use the 20-millimeter cannon to achieve desired effects against such targets. Assuming that each pilot can destroy at least one vehicle by strafing (20-millimeter rounds treated as a single "deliverable munition"), then the planner can determine a new maximum effects value as follows:

$(P_{effects})_{max}$ = (5 deliverable munitions) / (1 munition per DPI) = 5 DPIs

<center>Measuring Effects Persistence for a Force
Containing Multiple Aircraft</center>

The total effects persistence of a force is equal to the sum of its individual aircraft effects persistence values:

<div style="border:1px solid black; padding:1em;">

Force $P_{effects}$ = $(P_{effects})_1$ + $(P_{effects})_2$ ...+ $(P_{effects})_n$

where   *Force $(P_{effects})$ = attack force total effects persistence*

   $(P_{effects})_n$ = effects persistence for n^{th} aircraft

</div>

Unlike area-time persistence for which redundancy of presence occurs among aircraft, effects persistence is cumulative because two aircraft do not normally provide redundancy of lethal effects against common DPIs.

<center>Presenting Persistence Data</center>

To provide a useful decision tool, one must present the measures of dynamic targeting persistence in a useable form that enables decision-makers to assess an attack force's total persistence capability. However, one should not simply add or multiply the values for area-time persistence ($P_{area\text{-}time}$) and effects persistence ($P_{effects}$) to achieve a single overall index for each aircraft or for the entire force. In determining $P_{area\text{-}time}$, a planner has quantified a single aircraft's ability to provide presence, and in determining $P_{effects}$, the planner has quantified that aircraft's ability to provide effects. The value resulting from combining the "presence" value with the "effects" value is invalid because

<center>57</center>

each weapon cannot provide independent area-time persistence unless the strike force only provides one effect per aircraft. The combined value would mask flexibility attained by providing effects with multiple aircraft.

For instance, assume that a force of twelve F-16s could provide dynamic targeting persistence by orbiting on-station with two GBU-31 JDAM bombs each. A single B-1 bomber carrying twenty-four GBU-31 JDAMs could potentially achieve equivalent effects ($P_{effects}$). If the sum of area-time persistence ($P_{area-time}$) for all twelve F-16s was equal to that of the B-1, then a total presence-plus-effects persistence value would also be equal, implying that persistence capabilities of the two forces is equal. However, the force of multiple fighters provides flexibility to attack many targets simultaneously, a capability unachievable by the single bomber that must provide effects sequentially. Additionally, the B-1 enjoys a huge combat radius advantage over each F-16 in the strike force allowing exclusive access to distant targets. Use of a single total persistence value to compare these very different forces would mask their unique capabilities regarding area-time persistence.

Figure 18 provides a sample format in which to present dynamic targeting persistence data for analysis, providing key persistence information that a decision-maker can use to compare dynamic targeting force options. Of course, one can tailor the format depending upon which values possess key importance for a given scenario.

```
┌─────────────────────────────────────────────────────────────────────────────┐
│          Dynamic Targeting Persistence Capabilities for Aircraft Type and Scenario │
│                                                                               │
│  Assumptions:                                                                 │
│         Describe assumptions used for persistence analysis (fuel availability, etc.) │
│                                                                               │
│  Force Persistence Values (considers overlapping persistence):                │
│         Number of Aircraft                              _____ aircraft       │
│         Maximum Area-Time Persistence, Force $P_{area-time}$      _____ nm²-hr │
│         Maximum Effects Persistence, Force $P_{effects}$          _____ DPIs  │
│                                                                               │
│  Persistence Values per Aircraft:                                             │
│         Maximum Instantaneous Combat Radius, $R_{inst\ (max)}$   _____ nm     │
│         Maximum Time on Station, $t_{on-station\ (max)}$         _____ hrs    │
│         Maximum Area-Time Persistence, $P_{area-time}$           _____ nm²-hr │
│         Maximum Effects Persistence, $P_{effects}$               _____ DPIs   │
│                                                                               │
│  Attachments:                                                                 │
│         Area Coverage Chart Overlay                                           │
│         Area-Time Persistence Graph                                           │
│         Persistence Calculations                                             │
│                                                                               │
└─────────────────────────────────────────────────────────────────────────────┘
```

Figure 18. Sample Format for Dynamic Targeting Persistence Information

Comparing F-15E and F-16 Dynamic Targeting
Persistence Capabilities

The following analysis compares the dynamic targeting persistence capabilities of

F-15E and F-16 aircraft using the persistence measurement methodology developed

during this research. As illustrated during development of the persistence measurement

methodology, force persistence capability is heavily scenario dependent. The following

force comparison is intended to provide a broad understanding of F-15E and F-16

persistence capabilities and, more importantly, to demonstrate practical application of

persistence measurement theory in a specific dynamic targeting environment.

The first step in the comparison establishes the notional scenario. The scenario is purposely very general in order to make a broad comparison, but it is also specific enough to require detailed analysis. The available fuel quantity is limited within the scenario in order answer the primary research question.

The second step in the comparison includes a brief capabilities analysis for F-15E and F-16 aircraft. This overview focuses upon capabilities that directly influence dynamic targeting persistence, including the variables discussed during formula development. The analysis assumes that remaining capabilities for both aircraft types are sufficient to accomplish the mission presented in the scenario.

The third step is measurement and comparison of persistence for a flight of F-15E aircraft and a flight of F-16 aircraft in the dynamic targeting mission scenario, including measurement of individual aircraft persistence and force persistence. The product of this analysis will be a comparative report presented in a format similar to that shown in figure 18.

The study assumes that both F-15E and F-16 aircraft types are available to planners for mission tasking. The USAF planners analyze availability issues during the Air Expeditionary Force planning construct in which various types of units are tasked to be "on call" for a given period (currently four months). Each on-call period typically provides joint force commanders at least one F-15E squadron and one F-16 squadron with which to accomplish various missions. Before a squadron is assigned to an Air Expeditionary Task Force, which is the tailored force drawn from a pool of deployable Air Expeditionary Force units, considerations such as aircraft readiness, personnel readiness, maintenance issues, and operations costs have been carefully analyzed. This

study assumes that planners have accomplished such analysis, that F-15E and F-16 aircraft are available for tasking, and that the planner must decide which type provides maximum dynamic targeting coverage given a limited amount of fuel.

Scenario

In this notional scenario, a planner must determine whether a force comprised of F-16 aircraft can provide greater persistence than a force comprised of F-15E aircraft when accomplishing the same X-AI mission with an equal amount of fuel available to each force. The F-15E and F-16 squadrons operate from the same airbase, which is 100 nautical miles from the nearest hostile territory (see figure 19) where the on-station location is located. Other airbases suitable for emergency landing exist within a 10-minute flight of the home base.

Forecasters expect fair weather in the region during the on-station period, with 30 to 50 percent cloud coverage at low to medium altitude and no precipitation. "Standard day" temperatures (15°C/59°F at sea level; -35°C/-31°F at 25,000 feet mean sea level) and calm winds exist at all altitudes.

Allied forces currently maintain air supremacy throughout the planned operational area, but all fighter aircraft must carry air-to-air missiles for self-protection. Allied forces have suppressed known surface-to-air threats, but aircraft must carry internal countermeasures (chaff and flares). Electronic attack pods are not required for the mission. For tactical mutual support and redundancy in case an aircraft has a problem, fighter aircraft must depart, recover, and loiter in flights containing at least two aircraft, which flight leads may split during periods of target attack.

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Targets expected during the six-hour vulnerability period include vehicles, equipment, and unhardened facilities. Potential targets exist throughout hostile terrain out to a distance of greater than 700 nautical miles from the base of operations, and analysts do not expect targets to emerge on friendly terrain. Planners assess that 500-pound-class weapons or larger will sufficiently effect expected target types, and risk of collateral damage near some potential targets requires use of precision (<10 meters circular error probable) or near-precision weapons (<20 meters circular error probable). Due to partial cloud cover, which may hinder laser guidance, aircrews plan to employ a mix of laser-guided bombs and global positioning system (GPS) guided bombs. Strafing attacks will adequately effect some, but not most, target-types expected by analysts.
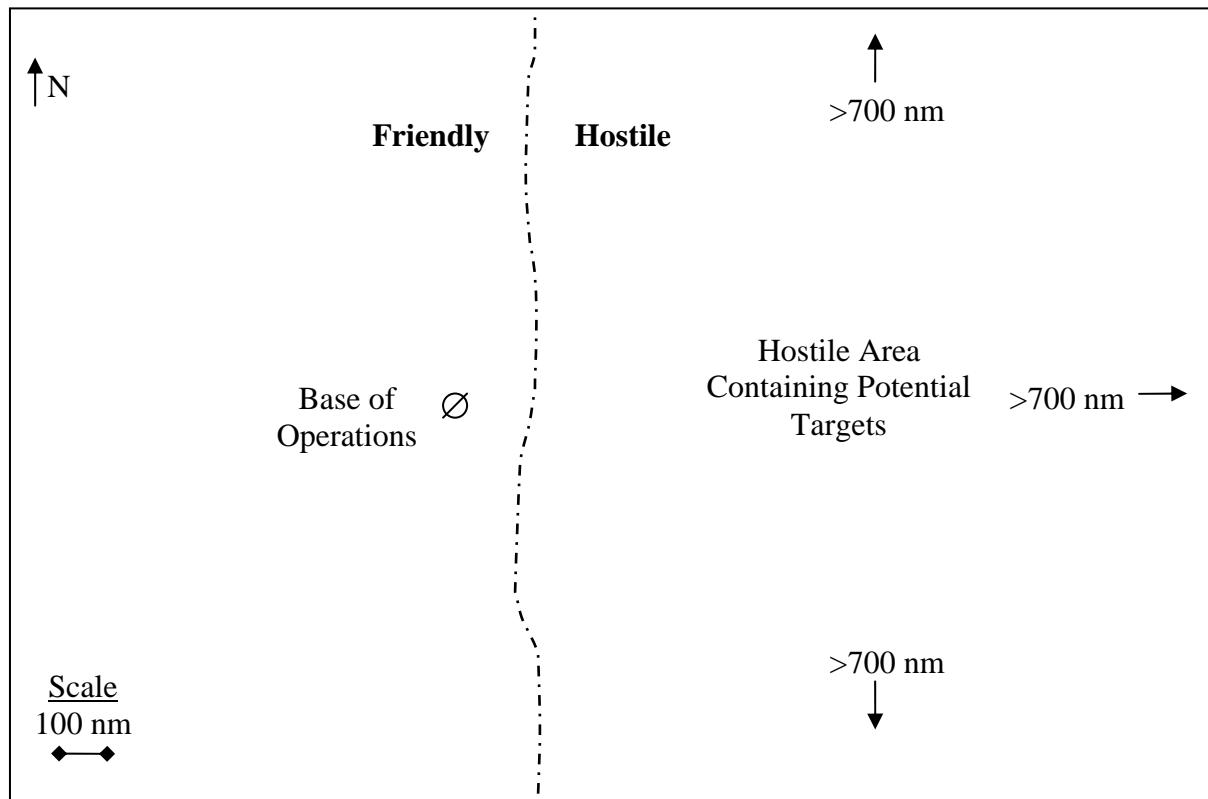

Figure 19. Notional Scenario for F-15E/F-16C Persistence Comparison

Fuel supply is very limited, and the entire X-AI aircraft force will receive a 100,000 pound total fuel quantity, which includes fuel received before aircraft start and during air refueling. This amount does not include fuel consumed by the air refueling aircraft or other receivers utilizing the same air refueling aircraft. Commanders have directed aircrews to conserve fuel using maximum range and maximum endurance procedures as appropriate.

The planner must analyze F-15E capabilities using the following standard configuration loadout:

    1. Conformal fuel tanks

    2. Two external wing fuel tanks

    3. Four GBU-12 laser guided bombs

    4. Four GBU-38 GPS guided bombs

    5. Four air-to-air missiles (2 AIM-120 AMRAAMs + 2 AIM-9 Sidewinders)

    6. Targeting and navigation pods

With a full fuel load, such an F-15E weighs 78,996 pounds and has a drag index of 91. An aircraft's drag index varies based upon its number and type of external stores, providing a means to account for drag caused by these stores when using aircraft performance charts.

The planner must analyze F-16 capabilities using the following standard configuration loadout:

    1. Two external wing fuel tanks

    2. Two GBU-12 laser guided bombs

    3. Two GBU-18 GPS guided bombs

4. Two air-to-air missiles (1 AIM-120 AMRAAM + 1 AIM-9 Sidewinder)

5. Targeting pod

With a full fuel load, such an F-16C weighs 29,844 pounds and has a drag index of 171. The F-16 drag index system differs from the F-15E drag index system, so one should not use the indices for direct comparison. However, planners similarly apply F-15E and F-16 drag indices when evaluating their respective aircraft performance charts.

Both types of aircraft will accomplish the mission at 25,000 feet mean sea level, unless analysis reveals that another altitude provides significant advantage. This altitude is relatively high for heavily loaded versions of both F-15Es and F-16s. As altitude increases, aircraft sacrifice maneuverability and close proximity to ground targets, but increase fuel efficiency and distance from surface-to-air threats. Unguided bomb accuracy decreases dramatically with altitude increase, but the bomb types used in this scenario provide desired effects when employed from 25,000 feet.

Aircraft Capabilities Analysis

The specific airframe versions used for this comparison include the F-15E Strike Eagle (figure 20) equipped with Pratt and Whitney F100-PW-229 engines and the Block 52 F-16C Fighting Falcon (figure 21), also equipped with the Pratt and Whitney F100-PW-229 engine. These represent the most advanced versions of F-15E and F-16 aircraft operated by the USAF today.

Airspeed Capabilities

F-15E and F-16 aircraft possess similar airspeed capabilities applicable to air-to-ground employment. Though the F-15E's maximum airspeed of Mach 2.5 exceeds the

F-16's maximum airspeed of Mach 2.0, aircrews typically execute normal air-to-ground missions at sub-mach airspeeds unless short bursts of speed are necessary for threat evasion (USAF Fact Sheet F-15E 2007, 2; USAF Fact Sheet F-16 2007, 2). Both the F-15E and F-16 must use afterburner to achieve and maintain supersonic (Mach 1.0+) airspeeds, an extremely fuel-inefficient event, and both aircraft have airspeed limitations well below Mach 2.0 when carrying external stores such as bombs, fuel tanks, missiles, and associated carriage hardware.

Figure 20. F-15E Strike Eagle
Source: Lee O. Tucker, Ruling the Skies, Air Force Link Web Site, 18, http://www.af. mil/photos/index.asp?galleryID=9&page=18 (accessed 7 November 2007).

Figure 21. F-16C Fighting Falcon
Source: Scott Reed, Over Southwest Asia, Air Force Link Web Site, 26, http://www.af. mil/photos/index.asp?galleryID=38&page=26 (accessed 7 November 2007).

For an F-15E configured as described above, maximum range and maximum endurance airspeeds are 450 knots true airspeed (KTAS) and 390 KTAS, respectively, when operating at 25,000 feet mean sea level (T.O. 1F-15E-1-1 2005, B5-12). For an F-16C configured as described above, maximum range airspeed is 400 KTAS and maximum endurance airspeed is 320 KTAS when operating at the same altitude (T.O. 1F-16CM-1-1, B5-40). Both aircraft can deliver GBU-12 and GBU-38 bombs at maximum range airspeed or maximum endurance airspeed if the tactical situation permits.

Table 1. Max Range Airspeed and Max Endurance Airspeed, F-15E
and F-16C, 25,000 Feet Mean Sea Level

	F-15E, Drag Index = 91	F-16C, D.I. = 171
Max Range Airspeed, $v_{\text{max range}}$	450 KTAS (0.75 mach)	400 KTAS (0.67
Max Endurance Airspeed, $v_{\text{max endure}}$	390 KTAS (0.65 mach)	320 KTAS (0.53

Fuel Capacity and Consumption

Though the F-15E's two-engine configuration and large fuel capacity provide range and payload advantages, the F-16's single-engine design provides a notable fuel efficiency advantage. The F-15E's internal fuel storage capacity is 13,511 pounds of JP-8 fuel, and its conformal fuel tanks (CFTs) add 9,835 pounds of capacity (T.O. 1F-15E-1-1 2005, B1-5). CFTs are standard on all USAF F-15E aircraft and are non-jettisonable during flight. The Strike Eagle can also carry three 610-gallon external tanks containing up to 4,148 pounds of fuel each (T.O. 1F-15E-1-1 2005, B1-7). These external tanks, unlike the CFTs, are jettisonable during flight. Each F-15E's total fuel capacity with all tanks loaded is 35,790 pounds, and the most common USAF combat configuration includes CFTs and external wing tanks for a total fuel capacity of 31,642 pounds. The combat-configured F-15E described in the research scenario can achieve a maximum endurance fuel flow of 8,000 pounds-per-hour at 25,000 feet mean sea level (T.O. 1F-15E-1-1 2005, B6-5). F-15E maximum range fuel flow under the same conditions is 9,000 pounds-per-hour (T.O. 1F-15E-1-1 2005, B5-50). Combat fuel flow at similar altitudes increases to about 12,000 pounds-per-hour in stabilized level flight when increasing throttle settings for evasive action or other maneuvering inefficiencies, and can be much higher if afterburner is applied (T.O. 1F-15E-1-1 2005, B9-31).

The F-16C's maximum internal fuel load is 7,100 pounds (Jackson 2007, 818).

The aircraft can also carry an external centerline fuel tank containing up to 2,000 pounds

of fuel and two wing tanks containing up to 2,500 pounds each (Jackson 2007, 818), all

of which can be jettisoned during flight. Though F-16 conformal fuel tanks exist, USAF

aircraft are not fitted with them. Each F-16's total fuel capacity with all external tanks

loaded is 14,100 pounds, and the most common USAF combat configuration includes

two external tanks for a total capacity of 12,100 pounds. The combat-configured F-16C

described in the research scenario can achieve a maximum endurance fuel flow of 3,100

pounds-per-hour at 25,000 feet mean sea level (T.O. 1F-16CM-1-1 2007, B5-40). F-16C

maximum range fuel flow under the same conditions is 3,500 pounds-per-hour (T.O. 1F-

16CM-1-1 2007, B5-40). Combat fuel flow at similar altitudes increases to about 6,000

pounds-per-hour in stabilized level flight if significant maneuvering or acceleration is

required and increases greatly if afterburner is applied (T.O. 1F16CM-1-1 2007, B5-34).

Table 2 summarizes F-15E and F-16 fuel capacities and consumption rates. All weight

measurements represent pounds of JP-8 fuel.

	F-15E	F-16C
Internal Fuel Capacity	13,550 lbs	7,160 lbs
Conformal Fuel Tank Capacity	9,800 lbs	N/A
External Wing Tank Capacity	4,100 lbs ea	2,420 lbs
External Centerline Tank Capacity	4,100 lbs	1,890 lbs
$Q_{capacity}$, Internal (+ CFT if applicable) + 3 External Tanks	35,550 lbs	13,890 lbs
$Q_{capacity}$, Internal (+ CFT if applicable) + 2 External Tanks	31,450 lbs	12,000 lbs
$Q_{capacity}$, Internal (+ CFT if applicable)	23,300 lb	7,160 lbs
Maximum Range Fuel Flow, $FF_{max\ range}$	9,000 pph	3,500 pph
Maximum Endurance Fuel Flow, $FF_{max\ endure}$	8,000 pph	3,100 pph

F-15E and F-16C Persistence Measurement
and Comparison

In order to compare persistence, the following analysis will first calculate F-15E

capabilities given the scenario constraints then calculate F-16C capabilities given the

same constraints.

F-15E Area-Time Persistence

One can calculate maximum instantaneous combat radius and area coverage per

aircraft using the formulas developed previously:

$(R_{inst})_{max} = 0.5\ (v_{max\ range})(\ Q_{capacity} - Q_{recovery} - Q_{reserve})\ /\ (FF_{max\ range})$

$(A_{inst})_{max} = 3.14\ (R_{inst})_{max}{}^{2}$

Tables 1 and 2 provide maximum range airspeed, $v_{max\ range}$, and aircraft fuel capacity,

$Q_{capacity}$. The planner calculates recovery fuel quantity, $Q_{recovery}$, using the 100 nautical

miles distance between home base and the on-station location. The F-15E reserve fuel

quantity, $Q_{reserve,}$ is 2,400 pounds as dictated by regulation since suitable alternate

airfields exist within a 20-minute flight distance of the intended base of landing.

Following are the scenario values for each variable in the equations above:

$v_{max\ range}$ = 450 nm/hr (Table 1)

$Q_{capacity}$ = 31,450 lbs (Table 2 value with CFTs and two external tanks)

$Q_{recovery}$ = $(D_{recovery})(FF_{max\ range})\ /\ v_{max\ range}$

$\quad\quad$ = (100 nm)(9,000 lbs/hr) / (450 nm/hr)

$\quad\quad$ = 2,000 lbs

$Q_{reserve}$ = 2,400 lbs (dictated by regulation)

$FF_{max\ range}$ = 9,000 lb/hr (Table 2 value)

$\quad\quad$ With values for each of the dependent variables, the planner can calculate

$(R_{inst})_{max}$ and $(A_{inst})_{max}$ from the nearest on-station location:

$(R_{inst})_{max}$ = $0.5\ (v_{max\ range})(\ Q_{capacity} - Q_{recovery} - Q_{reserve})\ /\ (FF_{max\ range})$

$\quad\quad$ = 0.5 (450 nm/hr)(31,450 lbs – 2,000 lbs – 2,400 lbs) / (9000 lb/hr)

$\quad\quad$ = <u>676 nm</u>

$(A_{inst})_{max}$ = 3.14 [676 nm] ^{2}

$\quad\quad$ = 1,430,000 nm^2

Adjusting the $(A_{inst})_{max}$ value for area not containing potential targets (approximately 50

percent),

Hostile $(A_{inst})_{max}$ = 0.50 (1,430,000 nm^2)

$\quad\quad$ = <u>715,000 nm^2</u>

$\quad\quad$ As a reminder, $(R_{inst})_{max}$ is a theoretical value intended for maximum capability

comparison, not prediction. It represents a straight-line distance flown at max range

airspeed directly to and from the target without maneuvering. To predict execution, a

planner should reduce this value by a percentage appropriate to the tactical environment.

This example scenario does not provide sufficient details (safe passage routing, threat

locations, radar coverage, and others) to deliberately calculate such a reduction factor.
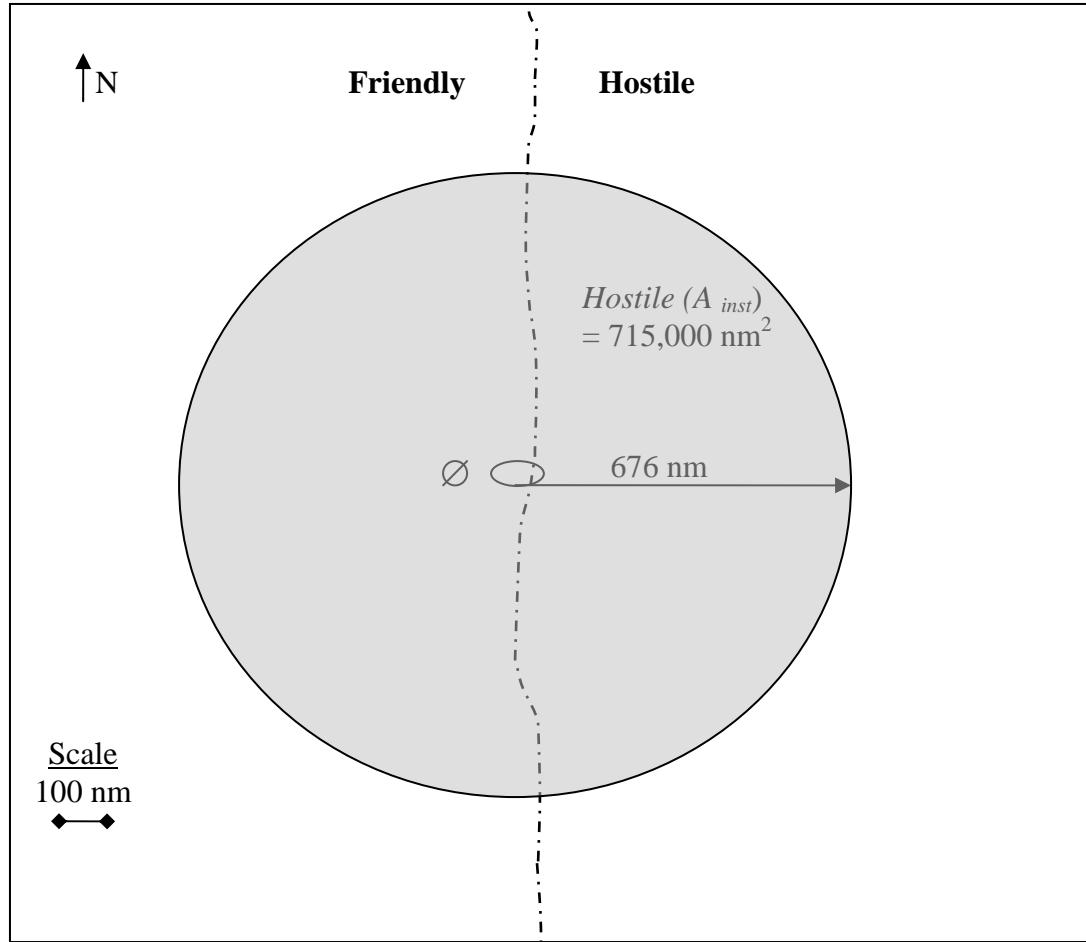

Figure 22. F-15E Map Overlay for Research Scenario

Knowing the on-station location, number of aircraft, and fuel available for each

aircraft, the planner can calculate the maximum potential time on-station with each

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aircraft's fuel allotment. Since two F-15Es must operate simultaneously, 50,000 pounds

of fuel is available for each one. The planner calculates maximum time on-station,

$t_{on\text{-}station\ (max)}$, as follows:

$t_{on\text{-}station\ (max)} = (Q_{total} - Q_{ground\ ops} - Q_{climb} - [(D_{departure})(FF_{max\ range}) / v_{max\ range}]$

$- [(D_{recovery})(FF_{max\ range}) / v_{max\ range}] - Q_{reserve}) / FF_{on\text{-}station}$

$= (50,000\ lbs - 3,000\ lbs - 2,800\ lbs - [(100\ nm - 34\ nm)(9,000\ lb/hr)$

$/ 450\ nm/hr] - [(100\ nm)(9,000\ lb/hr) / 450\ nm/hr] - 2,400\ lb) / 8,250\ lb/hr$

$= \underline{4.6\ hrs\ per\ aircraft}$

Each aircraft can only provide maximum coverage until it depletes on-station air

refueling availability, $Q_{air\ refuel}$, after which the area persistence decreases with fuel

consumption. One can estimate the time at which this occurs, t_{AR}, using the following

equation:

$t_{AR} = (Q_{air\ refuel} - Q_{ground} - Q_{climb} - Q_{departure}) / FF_{max\ endure}$

$Q_{air\ refuel} = Q_{total} - Q_{capacity}$

$= 50,000\ lbs - 31,450\ lbs$

$= 18,550\ lbs$

$t_{AR} = (18,550\ lbs - 3,000\ lbs - 2,800\ lbs - 1,320\ lbs) / 8,000\ lb/hr$

$= 1.4\ hrs$

The force's maximum instantaneous vulnerable area, *Force (A $_{inst})_{max}$*, is

represented by the sum of all shaded areas on figure 22. Since the two aircraft are co-

located, the following formula demonstrates that the second aircraft does not add area

persistence:

$Force\ (A_{inst})_{max} = (A_{inst})_1 + [(A_{inst})_2 - (A_{inst})_{shared}]$

$$= (715{,}000\ nm^2) + [(715{,}000\ nm^2) - 1.00(715{,}000\ nm^2)]$$

$$= \underline{715{,}000\ nm^2}$$

Similarly, since the two aircraft operate simultaneously, the following formula demonstrates that the second aircraft does not add time persistence:

$Force\ t_{on\text{-}station\ (max)} = t_{on\text{-}station\ (max)1} + [t_{on\text{-}station\ (max)2} - t_{on\text{-}station\ (max)\ shared}]$

$$= (4.6\ hrs) + [(4.6\ hrs) - 1.00(4.6\ hrs)]$$

$$= \underline{4.6\ hrs}$$

With a predicted (A_{inst}) values for the entire vulnerability period, a total area-time persistence value can be determined. Figure 23 depicts the area-time persistence chart for the force of two F-15E aircraft in this scenario. The shaded area on the chart represents the total area-time persistence for the entire force, calculated per the previously presented methodology:

$Force\ P_{area\text{-}time} = \sum Force\ A_{inst}$ from $t=0$ to $t=(t_{on\text{-}station})_{max}$

$= A_{inst}\ [t=0\ to\ 1.4] + A_{inst}\ [t=1.4\ to\ 4.6]$

$= (715{,}000\ nm^2)(1.4\ hrs) + 0.5(715{,}000\ nm^2)(3.2\ hrs)$

$= \underline{2{,}150{,}000\ nm^2\text{-}hrs}$
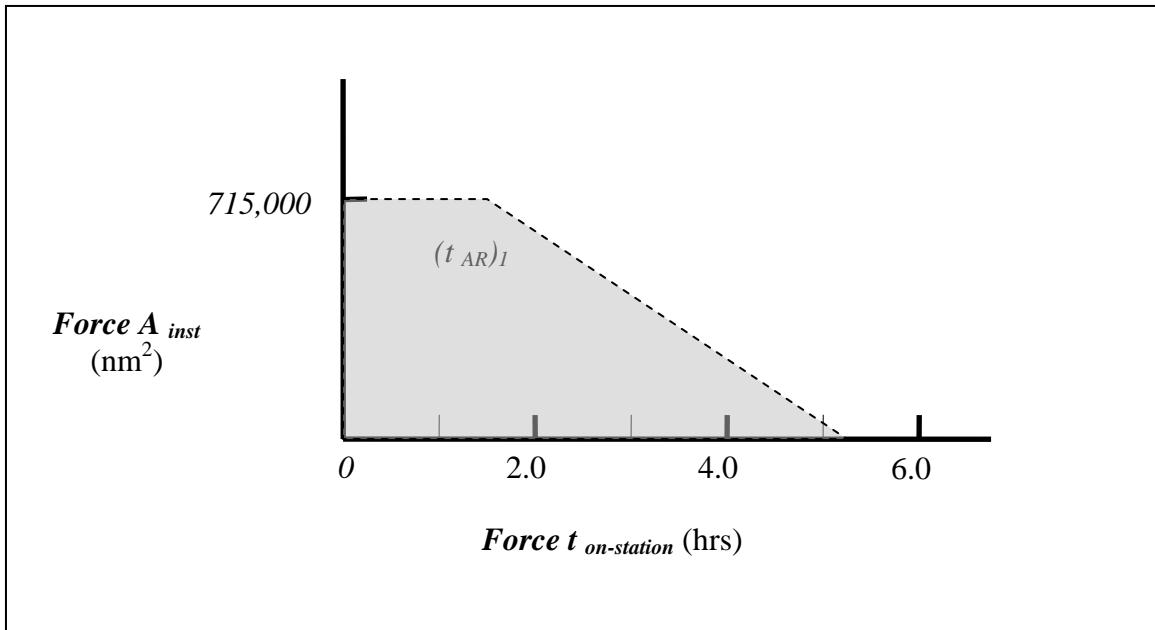
Figure 23. F-15E Area-Time Persistence Chart for Research Scenario

F-15E Effects Persistence

Measuring effects capabilities for this scenario is relatively easy. Each aircraft's ability to provide effects persistence is calculated as follows:

$(P_{effects})_{max}$ = (max # of deliverable munitions) / (# of munitions required to achieve desired effect on a single DPI)

= 8 deliverable munitions / 1 munition per DPI

= 8 DPIs

Force $P_{effects}$ = $(P_{effects})_1$ + $(P_{effects})_2$ ...+ $(P_{effects})_n$

= (8 DPIs) + (8 DPIs)

= 16 DPIs

F-16C Area-Time Persistence

In order to provide equivalent force effects persistence, *Force P*$_{effects}$, the F-16 force must include four aircraft (four DPIs each). The following calculations measure the four-ship area-time persistence using the same logic presented during the F-15E calculations, beginning with single-aircraft assumptions. First, the planner calculates instantaneous combat radius and instantaneous vulnerable area:

$(R_{inst})_{max} = 0.5\ (v_{max\ range})(\ Q_{capacity} - Q_{recovery} - Q_{reserve})\ /\ (FF_{max\ range})$

$(A_{inst})_{max} = 3.14\ (R_{inst})_{max}^{2}$

Following are the scenario F-16C values for each variable in the equations above:

$v_{max\ range} = 400$ nm/hr (Table 1 value with calm winds)

$Q_{capacity} = 12,000$ lbs (Table 2 value with two external tanks)

$Q_{recovery\ (min)} = (D_{recovery})(FF_{max\ range})\ /\ v_{max\ range}$

$= (100\ \text{nm})(3,500\ \text{lbs/hr})\ /\ (400\ \text{nm/hr})$

$= 875$ lbs

$Q_{reserve} = 1,200$ lbs (dictated by regulation)

$FF_{max\ range} = 3,500$ lb/hr (Table 2 value)

Applying the quantities above,

$(R_{inst})_{max} = 0.5\ (400\ \text{nm/hr})(12,000\ \text{lbs} - 875\ \text{lbs} - 1,200\ \text{lbs})\ /\ 3,500\ \text{lb/hr}$

$= \underline{567\ \text{nm}}$

$(A_{inst})_{max} = 3.14\ (567\ \text{nm})^{2}$

$= 1,010,000\ \text{nm}^{2}$

Maximum Vulnerable Hostile Area $= 0.5\ (1,010,000\ \text{nm}^{2})$

Hostile $(A_{inst})_{max} = \underline{505,000\ \text{nm}^{2}}$

Knowing the on-station locations, number of aircraft, and fuel available for each aircraft, the planner can calculate the time on-station per aircraft. With a fixed total of 100,000 pounds of fuel available and four F-16s, each aircraft has only 25,000 pounds available:

$$t_{\text{on-station (max)}} = (Q_{total} - Q_{ground\ ops} - Q_{climb} - [(D_{departure})(FF_{max\ range}) / v_{max\ range}]$$

$$- [(D_{recovery})(FF_{max\ range}) / v_{max\ range}] - Q_{reserve}) / FF_{on\text{-}station}$$

$$= (25{,}000\ lbs - 1{,}500\ lbs - 1{,}200\ lbs - [(100\ nm - 28\ nm)(3{,}500\ lb/hr)$$

$$/ 400\ nm/hr] - [(100\ nm)(3{,}500\ lb/hr) / 400\ nm/hr] - 1200\ lb) / 3200\ lb/hr$$

$$= \underline{6.1\ hrs\ per\ aircraft}$$

The planner must calculate t_{AR} for each on-station location to determine when instantaneous combat radius begins decreasing:

$$t_{AR} = (Q_{air\ refuel} - Q_{ground} - Q_{climb} - Q_{departure}) / FF_{max\ range}$$

$$Q_{air\ refuel} = Q_{total} - Q_{capacity}$$

$$= 24{,}600\ lbs - 12{,}000\ lbs$$

$$= 12{,}600\ lbs$$

$$t_{AR} = (12{,}600\ lbs - 1{,}500\ lbs - 1{,}200\ lbs - 630\ lbs) / 3{,}500\ lb/hr$$

$$= 2.6\ hrs$$

The F-16 force's maximum instantaneous vulnerable area, *Force $(A_{inst})_{max}$*, is represented by the shaded area in figure 24. As described previously, additional aircraft providing simultaneous, co-located presence add neither area nor time persistence.

$$\textit{Force } (A_{inst})_{max} = (A_{inst})_1 + [(A_{inst})_2 - (A_{inst})_{shared}] \ldots + [(A_{inst})_4 - (A_{inst})_{shared}]$$

$$= (505{,}000\ nm^2) + [0\ nm^2] + [0\ nm^2] + [0\ nm^2]$$

$$= \underline{505{,}000\ nm^2}$$

Force t $_{on\text{-}station\,(max)}$ = *t* $_{on\text{-}station\,(max)1}$ + [*t* $_{on\text{-}station\,(max)2}$ − *t* $_{on\text{-}station\,(max)\,shared}$]...+

[*t* $_{on\text{-}station\,(max)\,n}$ − *t* $_{on\text{-}station\,(max)\,shared}$]

= (6.1 hrs) + (0 hrs) + (0 hrs) + (0 hrs)

= 6.1 hrs
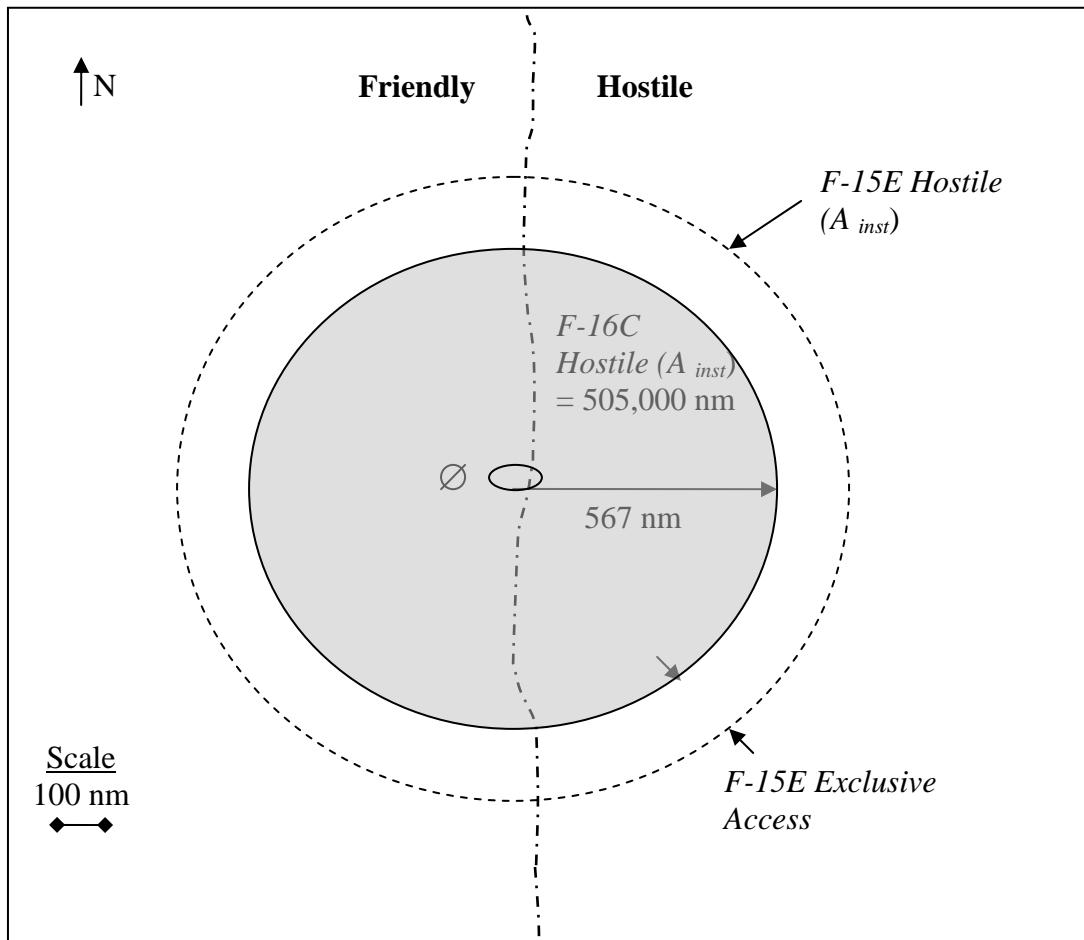
Figure 24. F-16C Map Overlay for Research Scenario

Figure 25 depicts the area-time persistence chart for the force of four F-16C aircraft.
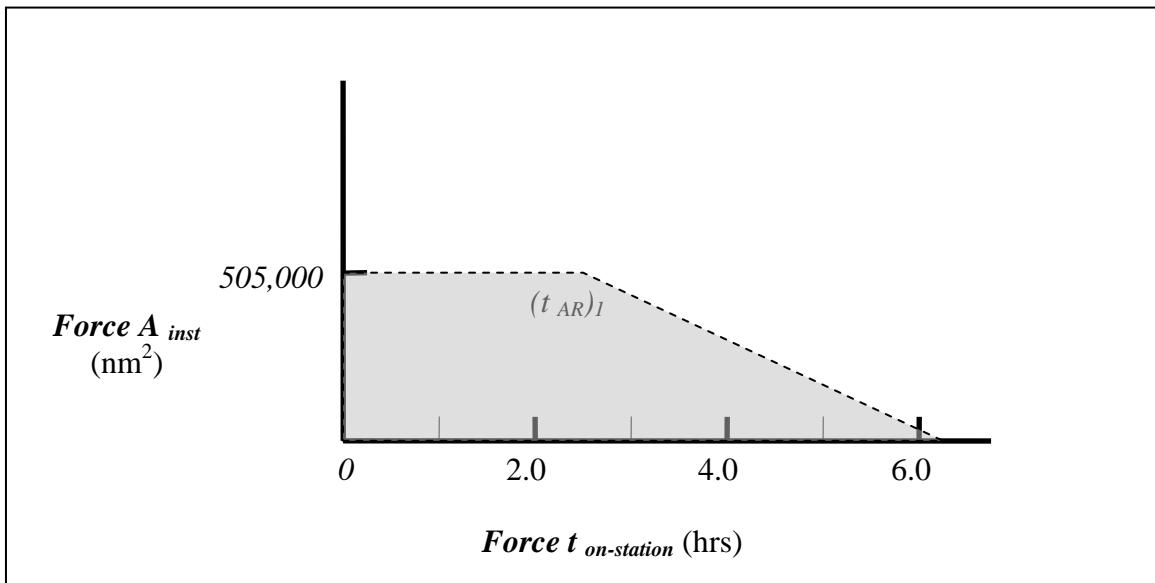
Figure 25. F-16C Area-Time Persistence Chart for Research Scenario

Force $P_{area\text{-}time}$ = $\sum$ Force A_{inst} from $t=0$ to $t=(t_{on\text{-}station})_{max}$

$= A_{inst} [t=0 \text{ to } 2.6] + A_{inst} [t=2.6 \text{ to } 6.1]$

$= (505{,}000 \text{ nm}^2)(2.6 \text{ hrs}) + 0.5(505{,}000 \text{ nm}^2)(6.1 \text{ hrs})$

$= \underline{2{,}850{,}000 \text{ nm}^2\text{-hrs}}$

F-16C Effects Persistence

$(P_{effects})_{max}$ = (max # of deliverable munitions) / (# of munitions required to achieve

desired effect on a single DPI)

$= 4 \text{ deliverable munitions} / 1 \text{ munition per DPI}$

$= 4 \text{ DPIs per aircraft}$

$Force\ P_{effects} = (P_{effects})_1 + (P_{effects})_2 \ldots + (P_{effects})_n$

$\quad = (4\ DPIs) \times (4\ aircraft)$

$\quad = 16\ DPIs$

Persistence Comparison Results

      Figure 26 summarizes results for the F-15E and F-16C dynamic targeting

persistence comparison.

Dynamic Targeting Persistence Capabilities, F-15E and F-16C, Research Scenario

Assumptions:
      Maximum 100,000 lbs of fuel available to each force
      (Remaining assumptions described in Chapter 4)

Force Persistence Values:	F-15E	F-16C
Number of Aircraft	2	4
Max Area-Time Persistence, nm^2-hr	2.15M	2.85M
Max Effects Persistence	16 DPIs	16 DPIs

Persistence Values per Aircraft:		
Maximum Instantaneous Combat Radius	676 nm	567 nm
Maximum Time on Station	4.6 hrs	6.1 hrs
Maximum Area-Time Persistence, nm^2-hr	715,000	505,000
Maximum Effects Persistence	16 DPIs	16 DPIs

Attachments:
      (Provided as Figures 21-24)

Figure 26. Dynamic Targeting Persistence Comparison Report, Research Scenario

      Given this fuel-limited scenario, an F-16 force can exceed the persistence

capability of an F-15E force. The "force persistence values" in the above report indicate

the degree of F-16 area-time persistence advantage given the scenario limitations along

with the fact that the F-16 force provides more aircraft, which allows greater employment

flexibility. The "persistence values per aircraft" indicate that each F-15E possesses

greater combat radius capability than each F-16, a characteristic that provides exclusive

access to distant areas containing potential targets as shown on figure 24. Each F-15E

also provides greater area-time persistence per aircraft, which indicates potential for

greater force persistence if not limited by fuel availability. Such capabilities may be

intuitive to a planner familiar with F-15E and F-16 operations, but the persistence

analysis quantifies each force's unique capabilities, providing a commander useable

information with which to make force selection decisions.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The analysis presented in chapter 4 answers the primary and secondary research

questions with two significant conclusions. First, dynamic targeting persistence is

quantifiable. Secondly, a force of F-16 aircraft can provide greater dynamic targeting

persistence than a force comprised of F-15E aircraft given the same total fuel quantity.

The primary research question is: With a limited amount of fuel, can a strike force

comprised of F-16 aircraft provide greater dynamic targeting persistence than a force

comprised of F-15E aircraft? In order to compare the persistence of two forces, a

researcher must first measure the forces' persistence. Though joint doctrine addresses

persistence and Air Force doctrine identifies it as a tenet of airpower, neither volume has

specifically defined the concept or provided guidance to measure it (AFDD 1 2003, 31).

This thesis defines persistence as "the cumulative period during which an aircraft can

access an area and provide desired effects," revealing three primary components of

persistence--time, area, and effects. Every combat aircraft system, whether manned or

unmanned, provides some level of persistence in a given scenario depending upon its

ability to maximize time, area, and effects, and each of these three elements is

measurable for an aircraft force delivering lethal effects. This research proposes

persistence evaluation using two measures: (1) area-time persistence, which indicates a

force's ability to provide presence, and (2) effects persistence, which indicates a force's

ability to deliver effects. By applying a specific system's capability data to the

calculations, one can quantify that system's dynamic targeting persistence for a given

scenario, affirmatively answering the secondary research question: Is dynamic targeting persistence quantifiable?

Application of F-15E and F-16C capability data into the newly developed methodology enables one to answer the primary research question but creates another secondary question--What are the capabilities and characteristics of F-15E and F-16 fighter aircraft? As determined during the research, persistence is a scenario-dependent characteristic. A system's persistence within one scenario changes if placed in another scenario. In order to limit scope, the researcher performed a persistence comparison using a single combat scenario that intentionally favored neither an F-15E nor F-16C force. The comparison was not intended to prove overall "persistence superiority" for either aircraft type, which would require lengthy consideration of multiple scenarios, but was performed to demonstrate that fuel efficiency can significantly influence persistence. The comparison also provided sample application of the newly developed persistence measurement methodology. For a given scenario, this analysis outlined the characteristics of F-15E and F-16C fighter aircraft relevant to dynamic targeting in the research scenario, answering the additional secondary research question.

The F-15E and F-16C force comparison revealed that, in a fuel-limited environment, F-16s could provide more overall persistence than F-15Es because of greater fuel efficiency per effect. Given an equal amount of fuel, the F-16 force's fuel efficiency enabled greater area-time persistence than an F-15E force possessing equal effects capability, just as an automobile's fuel efficiency enables greater travel distance than a less fuel-efficient automobile. Though an F-15E can deliver more than twice the number of munitions per aircraft, the F-16 force can provide more "effects per gallon."

The results suggest that, in a fuel-limited scenario, a commander may prefer an F-16 force if objectives favor maximum area-time persistence, simultaneous attacks, or rapid time-sensitive attacks enabled by numerous on-station locations potentially closer to emerging targets. However, the commander may prefer the F-15E force if objectives require engagement of distant targets accessible only by the Strike Eagle or delivery of weapons unique to the F-15E. Of course, a force containing both types could provide optimum levels of each capability. Whatever the objectives, the persistence measurement and comparison techniques developed in this study provide planners and commanders decision-quality information to make the best choice tailored to the situation.

Recommendations

Because neither joint doctrine nor Air Force doctrine currently defines persistence, the researcher recommends adding the proposed persistence definition to Joint Publication 1-02, *Department of Defense Dictionary of Military and Associated Terms*, and Air Force Doctrine Document 1-2, *Air Force Glossary*. Additionally, airpower doctrine should include expanded discussion of persistence and its elements--time, area, and effects.

The researcher also recommends review of this study by personnel charged with maximizing existing force persistence or developing persistent systems. The quantitative measurement techniques developed during this research expose the weakness of merely using maximum capability limits to compare systems and can enhance current means of measuring system persistence.

This research revealed three areas that provide potential for future research. First, techniques to measure non-lethal persistence require development. Measurement of area-

time persistence for aircraft that deliver non-lethal effects is probably similar to measurement of the same characteristic for aircraft that deliver lethal effects. However, quantitative analysis of non-lethal effects persistence provides a significant challenge due to targeting ambiguities.

Secondly, prediction of actual execution limits versus theoretical capabilities requires development of reduction factors that account for combat inefficiencies. For example, high power settings reduce combat radius, as justifiably encountered by an inexperienced pilot trying to maintain night tactical formation in combat. Similarly, indirect flight paths driven by the threat environment also decrease maximum range. This study calculated maximum theoretical values to make a force comparison, but additional research must provide scenario-based reduction factors to allow accurate prediction of realistic combat execution.

Finally, though the products of this research enable one to measure a force's persistence capabilities, further analysis is required for techniques to optimize a force's persistence capability. Such optimization could occur via force placement, external stores configuration, and or employment techniques.

The ability to predict dynamic targeting persistence in a given environment holds significant value not only in employment of dynamic targeting forces, but also in development of new systems that must maximize persistence of any kind. Only by fully understanding the components of persistence can air leaders fully exploit dynamic targeting capabilities.

GLOSSARY

Aircraft Combat Radius. The maximum distance an aircraft can travel away from its refueling source along a given course with normal combat load and return to its refueling source with appropriate fuel reserves.

Combat Radius (also, radius of action). "The maximum distance a ship, an aircraft, or a vehicle can travel away from its base along a given course with normal combat load and return without refueling, allowing for all safety and operating factors." (JP 1-02 2007, 444)

Deliberate Targeting. "Targeting that prosecutes planned targets that are known to exist in the operational environment with engagement actions scheduled against them to create the effects desired to support achievement of JFC objectives." (JP 3-60 2007, vii)

Desired Point Of Impact (DPI). "A precise point, associated with a target, and assigned as the center for a single unitary weapon to create a desired effect." (JP 1-02 2007, 158)

Dynamic Targeting. "Targeting that prosecutes targets identified too late, or not selected for action in time to be included in deliberate targeting." (JP 3-60 2007, GL-7)

High Payoff Target. "A target whose loss to the enemy will significantly contribute to the success of the friendly course of action." (JP 1-02 2007, 239)

On-Call Target. "Planned target upon which fires or other actions are determined using deliberate targeting and triggered, when detected or located, using dynamic targeting." (JP 3-60 2007, GL-11)

On-Station Time. "The time an aircraft can remain on-station. May be determined by endurance or orders." (JP 1-02 2007, 390)

Persistence. The cumulative period during which an aircraft can access an area and provide desired effects.

Scheduled Target. Planned target upon which fires or other actions are scheduled for prosecution at a specific time. (JP 3-60 2007, GL-12)

Time Sensitive Target. A JFC designated target or target type of such high importance to the accomplishment of the JFC's mission and objectives or one that presents such a significant strategic or operational threat to friendly forces or allies, that the JFC dedicates intelligence collections and attack assets or is willing to divert assets away from other targets in order to find, fix, track, target, engage, and assess it. (JP 3-60 2007, I-5)

Unanticipated Target. A target of opportunity that was unknown or not expected to exist in the operational environment. (JP 3-60 2007, GL-15)

Unplanned Target. A target of opportunity that is known to exist in the operational environment. (JP 3-60 2007, GL-15)

SUMMARY OF PERSISTENCE MEASUREMENT FORMULAS

$A_{inst} = (R_{inst})^2$

$(A_{inst})_{max} = \Pi\,[0.5\,(v_{max\ range})(Q_{capacity} - Q_{recovery} - Q_{reserve})\,/\,(FF_{max\ range})]^2$

$(A_{inst})_{opt} = \Pi\,[0.5\,(v_{max\ range})(Q_{current} - Q_{recovery} - Q_{reserve})\,/\,(FF_{max\ range})]^2$

$FF_{on\text{-}station} = [(t_{loiter})(FF_{loiter}) + (t_{attack})(FF_{attack})]\,/\,(t_{loiter} + t_{attack})$

$Force\ (A_{inst}) = (A_{inst})_1 + [(A_{inst})_2 - (A_{inst})_{shared}]... + [(A_{inst})_n - (A_{inst})_{shared}]$

$Force\ P_{area\text{-}time} = \sum Force\ A_{inst}\ from\ t{=}0\ to\ t{=}(t_{on\text{-}station})_{max}$

$Force\ P_{effects} = (P_{effects})_1 + (P_{effects})_2 ... + (P_{effects})_n$

$Force\ t_{on\text{-}station\ (max)} = t_{on\text{-}station\ (max)1} + [t_{on\text{-}station\ (max)2} - t_{on\text{-}station\ (max)\ shared}]... +$
$[t_{on\text{-}station\ (max)\ n} - t_{on\text{-}station\ (max)\ shared}]$

$P_{area\text{-}time} = \sum(A_{inst})_{opt}\ from\ [t{=}0]\ to\ [t{=}(t_{on\text{-}station})_{max}]$

$(P_{effects})_{max} = (max\ \#\ of\ deliverable\ munitions)\,/\,(\#\ of\ munitions\ required\ to\ achieve\ desired\ effect\ at\ a\ single\ DPI)$

$Q_{departure} = (D_{departure})(FF_{departure})\,/\,v_{departure}$

$Q_{departure\ (min)} = (D_{departure})(FF_{max\ range})\,/\,v_{max\ range}$

$Q_{ground\ ops} = (FF_{ground\ ops})(t_{ground\ ops})$

$Q_{on\text{-}station} = Q_{total} - Q_{ground\ ops} - Q_{climb} - Q_{departure} - Q_{recovery} - Q_{reserve}$

$Q_{recovery} = (D_{recovery})(FF_{recovery})\,/\,v_{recovery}$

$Q_{recovery\ (min)} = (D_{recovery})(FF_{max\ range})\,/\,v_{max\ range}$

$R_{inst} = 0.5\,(v_{mean})(Q_{current} - Q_{recovery} - Q_{reserve})\,/\,(FF_{mean})$

$(R_{inst})_{opt} = 0.5\,(v_{max\ range})(Q_{current} - Q_{recovery} - Q_{reserve})\,/\,(FF_{max\ range})$

$t_{AR} = (Q_{air\ refuel} - Q_{ground} - Q_{climb} - Q_{departure})\,/\,FF_{max\ endure}$

$t_{on\text{-}station} = Q_{on\text{-}station}\,/\,FF_{on\text{-}station}$

$t_{\text{on-station}} = (Q_{\text{total}} - Q_{\text{ground ops}} - Q_{\text{climb}} - Q_{\text{departure}} - Q_{\text{recovery}} - Q_{\text{reserve}}) / FF_{\text{on-station}}$

$t_{\text{on-station (max)}} = (Q_{\text{total}} - Q_{\text{ground ops}} - Q_{\text{climb}} - Q_{\text{departure (min)}} - Q_{\text{recovery (min)}} - Q_{\text{reserve}}) / FF_{\text{on-station (min)}}$

A_{inst} = *instantaneous vulnerable area*

$(A_{\text{inst}})_{\text{max}}$ = *maximum instantaneous vulnerable area*

$(A_{\text{inst}})_n$ = *instantaneous vulnerable area for n^{th} aircraft*

$(A_{\text{inst}})_{\text{opt}}$ = *optimum instantaneous vulnerable area*

$(A_{\text{inst}})_{\text{shared}}$ = *portion of vulnerable area also made vulnerable by other aircraft*

$D_{\text{departure}}$ = *distance flown during departure after climb*

D_{recovery} = *distance flown during recovery*

FF_{attack} = *mean fuel flow during attack*

$FF_{\text{departure}}$ = *mean fuel flow during departure*

$FF_{\text{ground ops}}$ = *mean fuel flow during ground operations, engine start to takeoff*

FF_{loiter} = *mean fuel flow during on-station loitering*

$FF_{\text{max endure}}$ = *fuel flow achieved at maximum endurance airspeed*

$FF_{\text{max range}}$ = *fuel flow achieved at maximum range airspeed*

FF_{mean} = *mean fuel flow*

$FF_{\text{on-station}}$ = *mean fuel flow during on-station operations (loiter and attack)*

$FF_{\text{on-station (min)}}$ = *minimum achievable fuel flow rate during on-station ops*

FF_{recovery} = *mean fuel flow during recovery*

Force (A_{inst}) = *attack force total instantaneous vulnerable area*

Force $P_{\text{area-time}}$ = *attack force area-time persistence during an on-station period*

Force (P_{effects}) = *attack force total effects persistence*

Force t $_{on\text{-}station\,(max)}$ = attack force maximum time on-station

P$_{area\text{-}time}$ = total area-time persistence during an on-station period

(P$_{effects}$)$_n$ = effects persistence for nth aircraft

Q $_{air\,refuel}$ = total quantity of fuel available per aircraft via air refueling

Q $_{capacity}$ = maximum aircraft fuel capacity

Q $_{climb}$ = fuel quantity consumed during climb (takeoff to arrival at cruise altitude)

Q $_{current}$ = current fuel quantity

Q $_{departure}$ = fuel quantity consumed during departure (post-climb to on-station)

Q $_{departure\,(min)}$ = minimum fuel consumption during departure

Q $_{ground\,ops}$ = fuel quantity consumed during ground ops (engine start to takeoff)

Q $_{on\text{-}station}$ = quantity of fuel available for on-station operations

Q $_{recovery}$ = fuel quantity consumed during recovery (station exit to landing)

Q $_{recovery\,(min)}$ = minimum fuel consumption during recovery

Q $_{reserve}$ = fuel quantity reserved for divert to an alternate airfield if required

Q $_{total}$ = total fuel quantity available per aircraft (initial fuel + air-received fuel)

R $_{inst}$ = instantaneous combat radius

(R $_{inst}$)$_{opt}$ = optimum instantaneous combat radius

(R $_{inst}$)$_{max}$ = maximum instantaneous combat radius

t $_{attack}$ = attack time

t $_{ground\,ops}$ = time consumed during ground operations, engine start to takeoff

t $_{loiter}$ = on-station loiter time

t $_{on\text{-}station\,(max)\,n}$ = maximum time on-station for nth aircraft

t $_{on\text{-}station}$ = on-station time

t_{AR} = *time from on-station arrival to air refueling non-availability*

$v_{departure}$ = *mean airspeed during departure*

$v_{max\ range}$ = *maximum range airspeed*

v_{mean} = *mean airspeed*

$v_{recovery}$ = *mean airspeed during recovery*

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